00188.27-01f

Benefits Assessment Compilation for En Route Data Exchange (EDX)

Tara J. Weidner

Tysen Mueller

Seagull Technology, Inc.

Prepared for:

National Aeronautics and Space Administration
Ames Research Center, Moffett Field, CA 94035

Under:

SRC Subcontract No. 99-0249, Task Order No. RTO-27 1266-100

NASA Prime Contract No. NAS2-98005

Seagull Project No. C188.27

December 2000 / Revised 8/01

Acknowledgment

This research was performed by Seagull Technology, Inc., as a subcontract to System Resources Corporation (SRC) for the National Aeronautics and Space Administration (NASA) Ames Research Center's Advanced Air Transportation Technologies (AATT) Project. The research was performed under the project management of Tara Weidner with assistance from Tysen Mueller, Goli Davidson, Lance Birtcil, George Couluris, and Jimmy Krozel. John Sorensen provided report editing.

This work represents the compilation and update of many previous data exchange benefits efforts performed by Seagull, dating back to 1996. Several of these previous efforts were performed for the FMS-ATM Next Generation (FANG) project with support from the Federal Aviation Administration (FAA) Aeronautical Data Link (ADL) Program under the leadership of Bill Blake and later Mike Hawthorne.

The authors appreciate the discussions, technical direction, and program lead of Rich Coppenbarger, manager of the En Route Data Exchange (EDX) project at NASA Ames Research Center. Additional thanks are extended to other key members of the NASA En Route Operations branch that provided guidance on various segments of this work, particularly Steve Green, Dave McNally, and Karl Bilimoria.

Table Of Contents

List Of Tables

List Of Figures

Executive Summary

Benefits Assessment Compilation for En Route Data Exchange (EDX)

Several National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), and international programs are identifying the ability and desirability of exchanging information between users and Air Traffic Management (ATM) service providers. Such data exchange, shown in Figure 1 is useful to ATM in enhancing surveillance and intent, augmenting and/or increasing the accuracy of currently available data. Indeed, the usefulness of such data has increased with new ATM Decision Support Tools (DSTs), which can utilize higher accuracy input data within their complex algorithms where prior cognitive processes would be overloaded. Enhancement of ATM DSTs supports implementation of advanced free flight concepts to provide increased user flexibility, capacity, and reduced delay. Data exchange can also be employed by airline users to support better situational awareness, strategic flight preferences, and fleet management. This study is a compilation and refinement of previously examined benefits mechanisms expected from en route data exchange (EDX). This report presents cross-comparable estimates, where currently available, based on updates of previous and ongoing work.

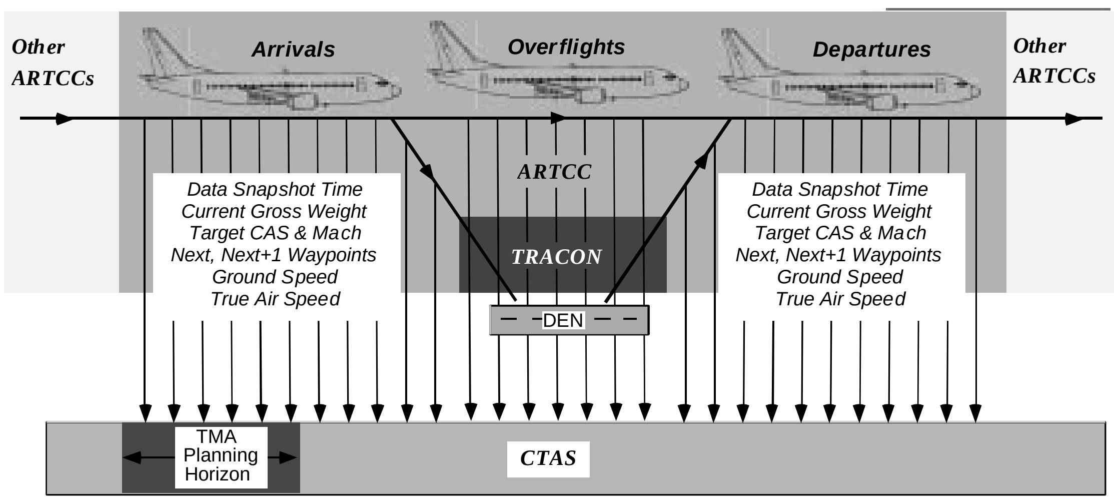


Figure 1 En Route Data Exchange can Improve ATM/DST Performance

The following evolutionary EDX scenarios were evaluated relative to two system baselines.

- **Passive Baseline** – Free Flight Phase 1 (FFP1) ATM decision support tools, including CTAS Traffic Management Advisor (TMA) and passive Final Approach Spacing Tool (pFAST), and the User Request Evaluation Tool (URET CCLD)
- **Active Baseline** – Enhanced FFP1, adding integrated CTAS En Route Descent Advisor (EDA) and conflict probe.

- **EDX1 -** Weather (wind/temperature) data exchange
- **EDX2 -** Weather, Aircraft Weight and Thrust/Drag Coefficients data exchange
- **EDX3 -** Weather, Weight, and En Route Speed Intent data exchange
- **EDX4 -** Weather, Weight, Speed Intent, and Threshold Crossing Speed Intent data exchange
- **EDX5 -** Weather, Weight, Speed Intent, and Next Two Waypoints data exchange
- **EDX6 -** Weather, Weight, and RTA/Speed Intent data exchange.

The NAS-wide benefits, assuming use at 37 US airports and limited to those that occur from DSTs operating in en route (ARTCC) airspace, are identified in Table 1. The $20M annual NAS-wide benefits (for either baseline) addresses only the limited benefit mechanisms identified in the table. Most of these annual benefits result from enabled direct departures ($12M) and related airport throughput and Center/TRACON delay distribution benefits (combined $7M-$10M). In particular, significant controller and pilot workload benefits expected from EDX have not been quantified, including overall safety enhancement with improved EDX surveillance, reduction in the need for corrective interruptions, reduced conflict probe alerts (especially missed and false alerts) and increasing controller confidence. Although these benefits may appear small, relative to those expected for a new ATM DST, it should be noted that implementation of EDX concepts requires only minor changes to existing or planned datalink, ATM DST, and aircraft FMS technologies, greatly reducing EDX costs.

Table 1 NAS EDX Benefits Matrix

37-Airport Annual Benefits ($000) Benefit Mechanism	Baseline	EDX 1 Wind, Temp	EDX 2 +Wt, thrust/drag	EDX 3 + Arr/Dep Spd Intent	EDX 4 +TH Xing speed	EDX 5 +next 2 waypoints	EDX 6 +RTA/ Spd Intent
Airport Throughput	Passive	0 hrs $0	16.7 hrs $1,614	32.8 hrs $3,167	NA	NA	Future
	Active	6.6 hrs $637	6.8 hrs $659	0 hrs $0	NA	NA	Future
Center/TRACON Delay Distribution	Passive	2.2 Mlbs $215	1.6 Mlbs $159	21.2 Mlbs $2,119	24.2 Mlbs $2.424	NA	Future
	Active	16.2 Mlbs $1,617	19.8 Mlbs $1,981	0 lbs $0	24.3 Mlbs $2,425	NA	Future
FMS Descent Speed Profile	Passive	NA	NA	NA	NA	NA	NA
	Active	Future (1)	Future (1)	Future (1)	NA	NA	11.3 Mlbs $1,129 (1)
Separation Assurance Interruptions	Passive	NA	NA	NA	NA	NA	NA
	Active	3.5 Mlbs $351	6.1 Mlbs $605	23.3 Mlbs $2,328	NA	3.9 Mlbs $298	Future
Enabled Departure Direct Routing	Passive	148 hrs 40.4 Mlbs $12,482 (3) (4)			NA	Future	NA
	Active	142 hrs 44.6 Mlbs $13,423 (3) (4)			NA	Future	NA

(1) EDX6 benefit assumes EDX1, EDX2, EDX3 data exchange in the baseline although these benefits are not quantified.
(2) EDX1-EDX5 reduced the number of missed alerts (MA) by 25%, false alerts (FA) by 7%, and overall conflict alerts by 10%.
(3) Includes EDX1, EDX2, and EDX3 data exchange benefits. Using Separation Assurance Interruptions Benefit ratios, 11%, 18%, and 71%, would be attributable to EDX1, EDX2 and EDX3, respectively.
(4) EDX benefits could be extended to enable arrival direct routes, with EDA picking up metered arrival direct routes in the Active Baseline.

Benefits Assessment Compilation for En Route Data Exchange (EDX)

Summary

Several National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), and international programs are identifying the ability and desirability of exchanging information between users and Air Traffic Management (ATM) service providers. Such data exchange, as depicted in Figure S.1, is useful to ATM in enhancing surveillance and intent, augmenting and/or increasing the accuracy of currently available data. Indeed, the usefulness of such data has increased with new ATM Decision Support Tools (DSTs), which can utilize higher accuracy input data within their complex algorithms where prior cognitive processes would be overloaded. Enhancement of ATM DSTs supports implementation of advanced free flight concepts to provide increased user flexibility, capacity, and reduced delay. Data exchange can also be employed by airline users to support better situational awareness, strategic flight preferences, and fleet management. This study is a compilation and refinement of previously examined benefits mechanisms expected from en route data exchange (EDX). This report presents cross-comparable estimates, where currently available, based on updates of previous and ongoing work. These benefits are limited to those that occur from DSTs operating in en route (ARTCC) airspace.

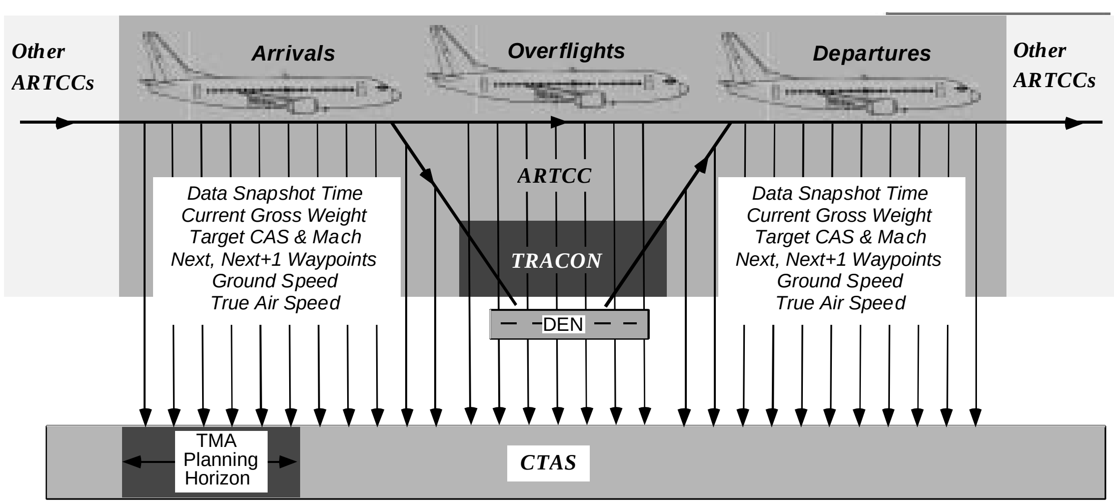


Figure S.1 En Route Data Exchange can Improve ATM/DST Performance

NASA Ames Research Center is developing air traffic control DSTs to enhance the capacity, efficiency, and flexibility of the National Airspace System (NAS) [1] and advance industry initiatives such as Free Flight [2]. En route decision support tools will assist controllers in the efficient management of air traffic within and between Air Route Traffic Control Centers (ARTCCs, also known as “Centers”). These tools will impact aircraft at all phases of Center airspace flight, including climb, cruise, and descent, with the goal of reducing deviations from the airspace user’s preferred trajectory. Currently, NASA’s Advanced Air Transportation Technologies (AATT) project is focused on developing advanced en route decision support tools such as the Traffic Management Advisor (TMA) [3] and the En Route/Descent Advisor (EDA) [4], part of the Center-TRACON Automation System (CTAS). TMA provides scheduling and sequencing at ARTCC metering fixes, while EDA provides controllers with conflict-free, fuel-efficient aircraft clearance advisories to meet the schedules provided by TMA. Additionally, EDA provides conflict probe capabilities that assist controllers in detecting and resolving aircraft conflicts, as well as accommodating user-requested route preferences.

For en route decision support tools to provide reliable conflict predictions and efficient schedules and sequences, a key technical requirement is to accurately predict future aircraft trajectories. The trajectory prediction accuracy of the Center decision support tools can be improved through the exchange of calibration, intent, user preference, and air traffic management (ATM) system state data between DSTs and the airspace users. This data exchange can be accomplished through the use of two-way datalink between ATM DSTs and the Flight Management System (FMS) on the airborne flight deck and between ATM DSTs and the Airline Operational Control (AOC)'s Computer System.

The En Route Data Exchange (EDX) project, part of NASA AATT, is tasked with investigating the operational benefit and feasibility of user-CTAS data exchange. The focus of initial EDX phases is to improve CTAS performance and accommodation of user preferences through near-term data exchange of airspace user information, such as aircraft state, performance, preference, and intent data, emphasizing current user equipage and capabilities. These plans include the real-time demonstration of initial user-CTAS data exchange [5]. Future phases will utilize two-way datalink capabilities with more advanced functionalities to facilitate advanced concepts such as four-dimensional (4D) user-ATM trajectory negotiation. The integration provided by these data exchanges will improve the accuracy of the en route decision support tools and FMS trajectory prediction models, allow ATM to receive and accommodate user preferences, and allow more informed collaborative decision making among the airspace users and ATM [6].

The overall goal of this effort is to provide a compilation and assessment of EDX-related benefits by combining past studies with new results based upon improved models and recent field tests of en-route trajectory prediction and ATM interaction. Over the past several years, both NASA and the FAA Airborne Datalink Program have sponsored various studies investigating benefits of user-ATM data exchange in the en-route and terminal airspace domains [7-14]. These preliminary studies have covered a wide variety of data exchange parameters, ATM baselines, and benefit mechanisms. This study is the compilation of these efforts and the first to provide a cross-comparable set of benefit estimates for a variety of EDX benefit mechanisms. It is noted that the studies compiled in the report date back to 1995 when analysis tools had some limitations. Each succeeding study was done with analysis tool refinement or had the benefit of using field trial data to calibrate the trajectory error parameters more accurately.

Study Cases

In this compilation, EDX benefits are computed by comparing ATM operations under various EDX cases relative to baseline systems as now defined.

Baseline Systems

Two en route airspace baselines are considered for EDX benefits analysis, representing different sets of ATM DSTs, as follows:

- **Passive Baseline** – The assumed Passive Baseline reflects en route operations aided by existing FAA Free Flight Phase 1 (FFP1) arrival metering and conflict probe tools. This includes the CTAS Traffic Management Advisor (TMA) to schedule and meter arrival flights, and a separate User Request Evaluation Tool (URET CCLD) conflict probe and trial-planning tool [15].

  TMA sets an arrival aircraft metering fix-crossing schedule at the Center/TRACON boundary and displays flight-specific delay advisories to the controller. The controller cognitively creates a strategy to absorb the specified delay to meet the TMA schedule.

  The conflict probe independently probes all en route airspace predicted trajectories and alerts controllers of potential separation assurance conflicts with a trial planner to assist in the development of effective resolution clearances. Because the metering conformance and conflict probe functions are not integrated in FFP1 operations, the conflict probe's performance suffers by being unaware of the controller metering conformance flight changes.

  Where TRACON operations are included, the Passive Baseline includes the passive Final Approach Spacing Tool (pFAST) to assist TRACON merging operations by providing runway assignments and runway sequence advisories to the controllers soon after the aircraft passes the arrival metering fix.

- **Active Baseline** - The assumed Active Baseline refers to future en route operations using integrated ATM metering and scheduling capabilities of the En Route/Descent Advisor (EDA) tools. EDA functionality is assumed to include integrated TMA arrival scheduling, EDA-calculated maneuver advisories to meet this schedule, and a conflict probe with both detection and trial planning capabilities. Additionally, unless otherwise noted, EDA is assumed to enable arrival direct routing when operationally feasible (departures continue to follow standard instrument departures, SIDs). The EDA maneuver advisories also assist controllers in formulating and executing a traffic delay strategy to conform to the TMA schedule, allowing the controller to quickly and accurately assess the impact of various delay methods. In order to generate maneuver advisories to controllers that result in conflict-free trajectories, the EDA tool includes a built-in conflict prediction/resolution capability. The conflict-probe function of EDA can also represent a stand alone conflict detection capability without the associated EDA advisories. The integration of the resulting metering conformance, flight changes with the conflict probe tool, and conflict resolution functions improves conflict probe intent performance, reducing false and missed alert rates.

  For TRACON operations, the Active Baseline includes the active Final Approach Spacing Tool (AFAST), which provides maneuver advisories to assist controllers in meeting the pFAST runway assignments and sequences. The AFAST assumption was only required for analysis of two EDX benefit mechanisms (airport throughput and Center/TRACON delay distribution). In another EDX benefit mechanism (FMS Descent Speed Profile) some basic data exchange is assumed.

EDX Data Parameter Categories

Past and ongoing efforts have identified a variety of parameters that would be useful to exchange between users and ATM [6,16-18]. See Appendix A for a review of relevant projects. Specific data parameters under consideration by various U.S. and European programs can be found in reference [18]. The specific subset of these categories, used in this study, follow the general categories. The primary EDX data categories are defined as follows:

<u>Aircraft-Specific Performance and Procedures</u>
These data includes engine/airframe performance characteristics and specific airline/pilot standard operating policies or practices, specific to each aircraft or aircraft type. These data are relatively static, and would not change on a flight-by-flight, day-to-day basis and thus, could be transmitted to ATM from the AOC. Relevant performance data include thrust and drag models and calibration factors, nominal ascent/descent rates, or envelopes as a function of speed profile. Relevant procedural data include typical turn rates or bank angles as a function of aircraft state and thrust management procedures or target ascent/descent rates.

<u>Flight-Specific Operating Factors</u>
These data affect flight performance and normally vary day-by-day from flight-to-flight. These data could be transmitted to ATM from the AOC pre-departure, and subsequently updated as appropriate. Flight-specific factors include, preferred takeoff and landing runways, acceptable delay to use preferred arrival and departure runway, approach/landing qualifications, required time of arrival (RTA) and FMS capabilities, and applicable cost index used for flight profile optimization.

<u>Aircraft State</u>
Aircraft state data include time-critical flight status information. These data should be transmitted from the aircraft periodically to ATM. State data include present aircraft position, altitude, velocity, heading, weight, actual navigation performance, and other trajectory dynamics (e.g., track angle and altitude change rate).

<u>Trajectory Intent</u>
These data describe FMS-calculated trajectory prediction and trajectory preferences. These data could initially be sent from AOC pre-departure in the form of the flight plan with additions/changes down linked from the aircraft to ATM. Intent data for a string of downstream four-dimensional trajectory control points (e.g., en route waypoints, Top of Descent, arrival metering fix) include each control point's name, 2-dimensional location, altitude, and crossing time. Additionally it may include the point type and the turn radius associated with a flight path transition. Intent data would also describe preferred speed and altitude profiles for climb, cruise and descent segments, and runway threshold crossing speed.

<u>Atmospheric Characteristics</u>
Meteorological data include aircraft in-flight measurements of atmospheric state and dissemination of atmospheric forecasts. In-flight atmospheric measurements could be transmitted from the aircraft to ATM periodically, with updated atmospheric predictions uplinked to aircraft. Atmospheric state data includes wind speed and direction, air temperature, air pressure, and turbulence reports.

EDX Evolutionary Cases

In this study, EDX encompasses four evolutionary cases (or data exchange configurations), which entail the exchange of data from all the aforementioned data parameter categories. Each case provides improved perception by supplementing the baseline DST trajectory prediction capabilities with EDX aircraft-specific flight information. The data are assumed to be down linked from the aircraft in real-time, although significant improvement may also result from AOC estimates, as previously discussed. Description of each EDX case follows:

- **EDX1 - Weather Data Exchange** – FMS downlink of airborne wind/temperature measurements. These real-time reports are used to upgrade ATM weather forecasts, used in DST trajectory prediction. Additionally, the improved meteorological forecast is disseminated providing a common weather forecast for ATM-FMS and AOC trajectory modeling.
- **EDX2 - Weather, Aircraft Weight and Thrust/Drag Coefficients Data Exchange** – EDX1 enhanced with user-provided flight-specific weight estimates as well as aircraft-specific thrust and drag coefficients. Such information is critical to modeling ascent/descent flight profiles.
- **EDX3 - Weather, Weight, and En Route Speed Intent Data Exchange** – EDX2 enhanced with user-provided aircraft-specific speed intent, including the climb/descent intended Mach/CAS speed profile and cruise speeds. ATM will attempt to accommodate this user preference.
- **EDX4 - Weather, Weight, Speed Intent, and Threshold Crossing Speed Intent Data Exchange** – EDX3 enhanced with user-provided arrival runway threshold crossing speed intent. Although this intent information is most useful to TRACON rather than en route ATM DSTs, it would be exchanged in the en route environment.
- **EDX5 - Weather, Weight, Speed Intent, and Next Two Waypoints Data Exchange** – EDX4 enhanced with downlink of the FMS's next two waypoints. Waypoint intent (names and/or locations) improves DST trajectory predictions when flight clearances are not recorded as flight plan amendments in the ARTCC computer.
- **EDX6 - Weather, Weight, and RTA/Speed Intent Data Exchange –** EDX2 enhanced with a simple real-time user-ATM "negotiation," where the EDA-calculated speed advisory is assumed to be replaced with the FMS user-preferred speed profile. Initially an arrival-metering fix required time of arrival (RTA) restriction, assumed to be calculated by TMA, is uplinked to the aircraft. The pilot then uses his on-board FMS RTA capability to generate an optimum speed profile to meet the metering fix time restriction. This FMS Mach/CAS descent speed profile is downlinked as an user-preferred trajectory. Full equipage consisting of FMS trajectory optimization and RTA guidance capabilities is assumed.

Potential EDX Benefit Mechanisms

Previous and ongoing NASA and FAA research have identified potential ATM and flight improvements and potential economic benefits expected under en route data exchange [7-10, 18]. The identified range of data exchange benefit mechanisms, limited to those occurring within the Center airspace environment, is summarized with references to relevant research efforts. The mechanisms are first described in terms of the underlying DST performance improvement, followed by the specific user economic benefit mechanisms. The particular benefit mechanisms evaluated, at least in part, within this report are noted with a checkmark (√).

Note that the information downlinked to ATM DSTs also can improve the performance of TRACON DSTs such as CTAS FAST. For example, threshold crossing speed would enable reduction of spacing buffer and inter-aircraft nominal spacing used by FAST; this would enhance runway throughput. However, these additional benefits are not summarized in this report.

Performance-based mechanisms

√ **Improvement of DST Trajectory Prediction Algorithms** – The core computational engine of DSTs involves the synthesis of individual aircraft trajectories. An estimate of an aircraft's trajectory out to some future waypoint provides an estimate of the aircraft's state as a function of time, and inherently models the flight crew's intent of steering the aircraft along that trajectory. ATM DST receipt of more reliable estimates of aircraft state and intent will improve the trajectory prediction accuracy of these trajectory synthesis algorithms, including future predictions of time and position, which support all ATM DST functions. State information such as current weight and speeds will improve upon default estimates used in trajectory modeling. Intent data, such as the next intended waypoint, will increase predicted trajectory adherence to the actual trajectory path over outdated flight plan intent. These improvements will afford increased performance in both ATM DST sequencing and scheduling algorithms, more accuracy in the conflict probe tool, and improved clearance advisories to resolve schedule and traffic conflicts. [19-24]

√ **Improvements to DST Scheduling Algorithms** – ATM relies on accurate predictions of flight trajectories to derive terminal area arrival and departure sequences and schedules. In the en route environment, this scheduling process can be evaluated by the ability of ATM to deliver flights to the arrival and departure metering fixes as scheduled. Inaccurate trajectories will upset the schedule integrity and subsequent delivery accuracy. Observations of flights during the 1997 CTAS TMA prototype field test identified a significant reduction in the arrival metering fix delivery error as compared to operations without TMA [22]. A further reduction of the delivery error is expected with data exchange trajectory prediction enhancement. Such improvements result in a more accurate ATM DST schedule, increase the efficiency of controller clearances to meet the schedule, and providing a smoother traffic stream for downstream operations.

√ **Improvements to Conflict Probe** – ATM relies on accurate predictions of flight trajectories within its conflict probe tool to accurately identify the location and nature of potential conflicts (i.e., separation assurance constraints appear to be violated). Feedback from the designers of CTAS' conflict probe functionality [21] suggests more accurate trajectory prediction obtained through the downlink of FMS intent data, particularly current horizontal route intent, could significantly reduce conflict probe prediction inaccuracies. Reduction of discrepancies between actual and predicted trajectories leads to higher accuracies in conflict predictions, reducing false and missed conflict alerts, as well as inappropriate resolution advisories

√ **Improvements to DST Maneuver Advisories** – ATM DSTs rely on accurate predictions of flight trajectories to accurately calculate aircraft-specific maneuver advisories to meet ATM

DST schedules, sequences, and conflict alert responses. More reliable trajectory prediction estimates lead to more appropriate, fuel-efficient, maneuvers that meet ATM separation assurance requirements.

√ **Accommodation of User Preferences** – ATM DST receipt of user preferences, such as climb/descent Mach/CAS schedules will allow more frequent accommodation of such speed schedules. Under low demand periods where ATM interventions are less necessary, this information would signify flight trajectory intent and thereby improve the conflict probe trajectory prediction accuracy. [21] Additionally, data exchange could allow users to receive ATM-system state data, as well as to communicate their preferred individual flight trajectories to ATM. Receipt of ATM-system state status information, such as capacity restrictions and delay estimates, may trigger changes in user preferences. Longer-term data-exchange concepts could enable the negotiation of user preferred trajectories.

- **Reduced Controller and Flight Crew Workload** - Improved trajectory prediction with air/ground data exchange, leads to more optimum and effective ATM clearances, leading to improved flight efficiencies (time and fuel) and tighter adherence to the imposed airspace restrictions. In general, with large trajectory prediction uncertainties controllers employ more conservative clearances that involve more fuel/time than necessary, in order to ensure that airspace restrictions are not violated. With improved trajectory prediction, more optimal clearances can be identified to resolve the conflict with user fuel/time savings. Both controller and flight crew workloads are reduced through reduced need for the development of strategies, issuing corrective advisories, and taking corrective maneuvers.

<u>Economic-based mechanisms</u>

√ **Increased Airport Throughput** – Reduced runway threshold separations (in excess of minimums) are expected from en route user-ATM data exchange as a result of better en route trajectory prediction facilitating leading to more accurate final controller advisories (outer marker) and reduced runway gaps from reduced variance in metering fix crossing times. Although Center improvements are likely less beneficial than TRACON trajectory accuracy improvements, such as utilization of downlinked threshold crossing speed in TRACON automation tools, some airport throughput benefit is still derived from En Route data exchange. This separation reduction leads to increased airport throughput and reduction in aircraft delay and delay propagation, especially during rush periods. [7-9]

√ **Improved Center/TRACON Delay Distribution** - Reduced variance in ATM DST scheduled arrival metering fix crossing results in efficiency benefits due to the ability to absorb delay more efficiently in Center airspace while still maintaining a given TRACON entry rate and airport landing rate. This delay is currently needed to absorb variability in arrival metering fix crossing time, which will be reduced under user-ATM DST data exchange. [7-9]

√ **More Fuel-Efficient Climbs/Descents** - The FMS downlink of its preferred altitude-speed profile to meet an arrival/departure fix crossing time allows more fuel efficient climbs/descents while maintaining airport capacity enhancements. The downlinked preferences would enhance DST-calculated altitude-speed profiles, saving aircraft fuel or direct operating cost in descent. [25-27]

- √ **Improved Separation Assurance ATM Interruptions** - Increased accuracy in DST predicted trajectories due to user-ATM DST data exchange, will lead to reduced or more efficient interventions on the part of the controller, both to meter the aircraft and to resolve separation conflicts. These controller actions, which take the aircraft off of its intended flight plan, are referred to as ATM interruptions. ATM interruptions of user preferred trajectories are improved by reducing the conflict probe tool's false and missed alerts. Data exchange will lead to more accurate and earlier identification of actual conflicts. With improved trajectory prediction, ATM would less frequently perceive aircraft to be incorrectly in conflict, resulting in fewer incorrect ATM flight interventions, and associated resolution fuel penalties. Additionally, improved traffic conflict prediction will include more accurate estimation of conflict geometry and speeds, leading to more efficient resolution maneuvers. [10,13]

- √ **Increased Direct Routing** – ATM automation tools assist controllers in accommodating user requests for more direct routing. These tools assess whether the direct route would save fuel, and facilitates the flight plan amendment process to execute the direct route clearance. Controllers frequently employ direct routes to resolve conflicts. However, controllers will typically not employ direct routing if it creates a new conflict. The identification of new conflicts is dependant upon ATM perception of closest point spacing between crossing paths and the buffers placed on the required minimum separation (currently 5 miles lateral spacing and 1000/2000 ft in altitude below/above FL290). Increased trajectory prediction accuracy with data exchange is expected to reduce the buffers that controllers will use, leading to fewer perceived conflicts. As a result, more direct routes may be employed saving aircraft time and fuel.[28]

- **Horizontal/Vertical Trajectory Optimization** – CTAS EDA is designed to allow both horizontal and vertical trajectory optimization with the relaxing of arrival metering fixes. These include shifting the Center/TRACON arrival metering fix or anchor point and the associated aircraft bottom of descent downstream as far as the runway outer marker. Thus arrival flights would realize a horizontal path reduction in the Center, by being able to fly more directly to the outer marker, and the vertical movement of the top of descent closer to the runway, would increase time spent at higher altitudes. Both mechanisms provide more fuel-efficient terminal area operations currently ascribed to EDA. However, data exchange may be required to fully enable such operations. [28-29]

- **Regional Airport Departure Release Times** - Major airports often have a significant number of their arrival traffic originating from nearby local or regional airports. The local Center, TRACON or major airport tower releases these flights as a part of a departure approval request process with the local towers. In releasing these departures, the Center or TRACON identifies a gap in the appropriate primary airport arrival stream into which the local aircraft can be merged. Once a gap is identified, the releasing facility estimates a release window that will allow the aircraft sufficient time to depart and merge into the primary arrival stream at the intended gap. The controller must predict the gap at a future time as well as estimate the flight time for the released aircraft to depart and reach the gap using current position display and flight strip data. Although DSTs (e.g., TMA) facilitates this process through trajectory prediction calculations, improved trajectory prediction, from state and weather data would enable controllers to more accurately evaluate gaps and release times.

This would enable more efficient scheduling of internal departures, reducing departure delay as well as airborne delay, propagation of this delay upstream, and other diversions necessary when aircraft miss their intended gap in the arrival stream. [30]

Analysis Process Overview

In general, the EDX benefit analyses methodology included in this and past studies employed the approach shown in Figure S.2. The process quantifies how improved DST calculations and ATM advisories leads to changes in ATM operations that are modeled over a typical day at one (or more) airport(s), to provide a basis for annual and NAS-wide benefit estimation. It employs four primary analysis steps.

1. **Technology Definitions** for each case are defined by associated parametric accuracy values and their improvements due to application of the technology. Statistical values for various parameters used to define the accuracy, or stochastic nature, of an aircraft trajectory are used. These values indicate, for each case, the estimated accuracy of DST trajectory predictions relative to the nominal trajectory followed.
2. **A Trajectory Prediction Accuracy Model,** based on Monte-Carlo simulation, uses these statistical parametric values to calculate DST expected timing and position errors for aircraft crossing key en route waypoints. These timing and position errors can be used in a conflict probe model and/or converted into excess spacing buffers, that would be used in ATM DSTs or imposed by air traffic controllers to protect against separation minima violations.
3. **An Air Traffic Operations Simulation**, typically over a day or rush period, combines the scenarios, parameters, and spacings defined for Baseline and EDX cases, with a traffic scenario and ATM operating procedures. The simulation computes measures of the DST improvements to scheduling/airport capacity, conflict probe flight interruptions, and overall flight fuel-efficiency.
4. **Economic models** are then used to convert the measured/simulated ATM performance improvements into user direct operating cost savings (time and fuel), which are extrapolated to annual and NAS-wide levels. It is important to note that not all benefits can be captured in direct operating cost metrics.

The specific methodology employed by each benefit mechanism assessed in this report is discussed in more detail in the following chapters.

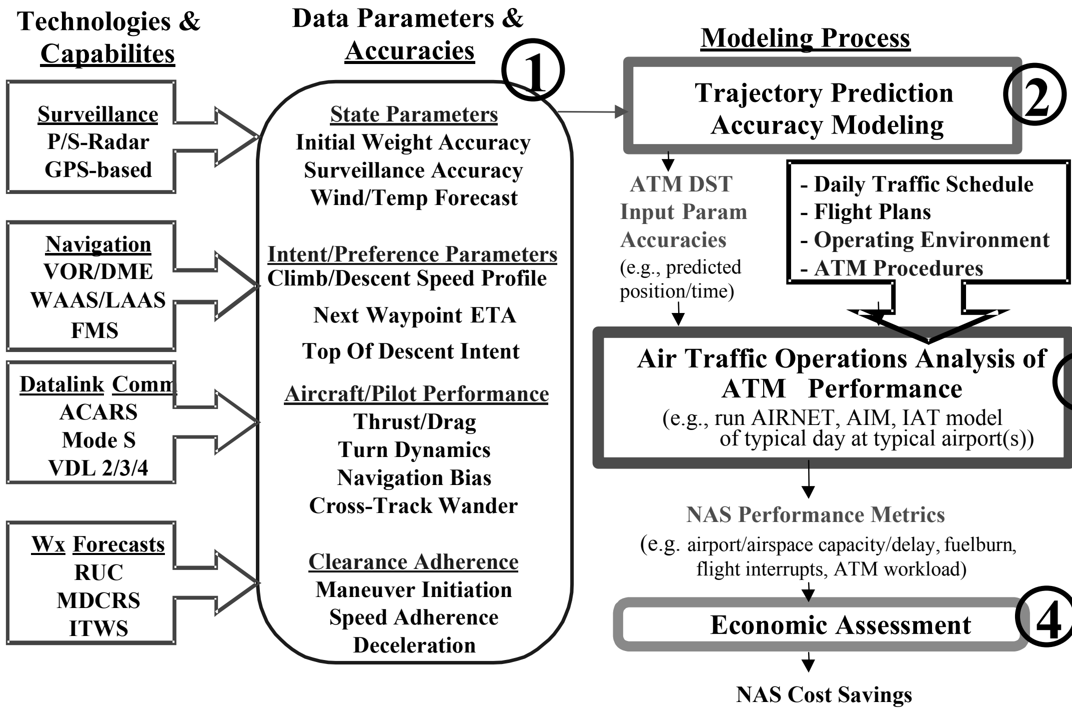


Figure S.2 EDX Study Analysis Process

Results Summary

Table S.1 and S.2 summarize the annual EDX benefits estimates for each EDX case included in this study for DFW (as a single airport in Table S.1) and a cumulative set of 37 Airports[1] (Table S.2). This set was chosen to represent high-demand NAS airports, include FAA FFP1 and Phase 2 deployment locations. The tables identify the incremental benefits of each successive data exchange case beginning with EDX1 compared to Passive and Active Baseline cases defined earlier. Note that for the Enabled Departure Direct Routing mechanism, EDX3 benefits include the benefits of earlier EDX1 and EDX2 data exchanges. Additional details for each of the five benefit mechanisms listed are found in later chapters of this report. Quantitative benefits are given for alternate metrics including time (hours), fuel (lbs), and cost ($). Cost estimates assume aircraft and airline crew and maintenance time rates, shown in Appendix C, and a value of $0.10 per lb for fuel. Fuel conservation is important, since fuel is a non-renewable resource and prices are subject to significant political forces. Shaded regions were not evaluated because they are either not relevant (NA) to en route DSTs or are not quantified to date, subjects for future work (Future).

[1] ATL, BDL, BNA, BOS, BWI, CLE, CLT, CVG, DCA, DEN, DFW, DTW, EWR, FLL, HOU, IAD, IAH, JFK, LAS, LAX, LGA, MCO, MDW, MEM, MIA, MSP, OAK, ORD, PDX, PHL, PHX, PIT, SAN, SEA, SFO, SLC, STL

Table S.1 DFW Annual EDX Benefits

DFW Annual Benefits ($000s) Benefit Mechanism	Baseline	EDX 1 Wind, Temp	EDX 2 +Wt, thrust/drag	EDX 3 + Arr/Dep Spd Intent	EDX 4 +TH Xing speed	EDX 5 +next 2 waypoints	EDX 6 +RTA/ Spd Intent
Airport Throughput	Passive	0 hrs $0	0.2 hrs $17.2	0.4 hrs $33.7	NA	NA	Future
	Active	0.1 hrs $6.9	0.1 hrs $7.0	0 hrs $0	NA	NA	Future
Center/TRACON Delay Distribution	Passive	0.2 Mlbs $13.6	0.1 Mlbs $10.0	1.3 Mlbs $133.8	1.5 Mlbs $153.1	NA	Future
	Active	1.0 Mlbs $102.1	1.3 Mlbs $125.1	0 lbs $0	1.5 Mlbs $153.1	NA	Future
FMS Descent Speed Profile	Passive	NA	NA	NA	NA	NA	NA
	Active	Future (1)	Future (1)	Future (1)	NA	NA	0.7 Mlbs $71.3 (1)
Separation Assurance ATM Interruptions (2)	Passive	NA	NA	NA	NA	NA	NA
	Active	0.2 Mlbs $19.0	0.3 Mlbs $32.6	1.3 Mlbs $125.8	NA	1.6 Mlbs $161	Future
Enabled Departure Direct Routing	Passive		8.1 hrs 2.2 Mlbs $683.1(3)		NA	Future	NA
	Active		7.8 hrs 2.4 Mlbs $734.6(3)		NA	Future	NA

Table S.2 NAS Annual EDX Benefits

37-Airport Annual Benefits ($000) Benefit Mechanism	Baseline	EDX 1 Wind, Temp	EDX 2 +Wt, thrust/drag	EDX 3 + Arr/Dep Spd Intent	EDX 4 +TH Xing speed	EDX 5 +next 2 waypoints	EDX 6 +RTA/ Spd Intent
Airport Throughput	Passive	0 hrs $0	16.7 hrs $1,614	32.8 hrs $3,167	NA	NA	Future
	Active	6.6 hrs $637	6.8 hrs $659	0 hrs $0	NA	NA	Future
Center/TRACON Delay Distribution	Passive	2.2 Mlbs $215	1.6 Mlbs $159	21.2 Mlbs $2,119	24.2 Mlbs $2.424	NA	Future
	Active	16.2 Mlbs $1,617	19.8 Mlbs $1,981	0 lbs $0	24.3 Mlbs $2,425	NA	Future
FMS Descent Speed Profile	Passive	NA	NA	NA	NA	NA	NA
	Active	Future (1)	Future (1)	Future (1)	NA	NA	11.3 Mlbs $1,129 (1)
Separation Assurance ATM Interruptions (2)	Passive	NA	NA	NA	NA	NA	NA
	Active	3.5 Mlbs $351	6.1 Mlbs $605	23.3 Mlbs $2,328	NA	3.9 Mlbs $298	Future
Enabled Departure Direct Routing	Passive		148 hrs 40.4 Mlbs $12,482 (3) (4)		NA	Future	NA
	Active		142 hrs 44.6 Mlbs $13,423 (3) (4)		NA	Future	NA

(1) EDX6 benefit assumes EDX1, EDX2, EDX3 data exchange in the baseline although these benefits are not quantified.
(2) EDX1-EDX5 reduced the number of missed alerts (MA) by 25%, false alerts (FA) by 7%, and overall conflict alerts by 10%.
(3) Includes EDX1, EDX2, and EDX3 data exchange benefits. Using Separation Assurance ATM Interruptions Benefit ratios, 11%, 18%, and 71%, would be attributable to EDX1, EDX2 and EDX3, respectively.
(4) EDX benefits could be extended to enable arrival direct routes, with EDA picking up metered arrival direct routes in the Active Baseline.

Of the over $20M NAS-wide annual quantified EDX benefits of Table S.2 for either baseline, the largest estimate results from enabling departure direct routing, which saves over $12M annually in a combination of time and fuel savings. Enabled direct routes could also be extended to cover arrivals, at an increase in benefits.

The next largest EDX benefits result from the related mechanisms of airport throughput and Center/TRACON delay distribution, savings $7M and $10M each per year, under Passive and Active Baselines, respectively. Improved EDX arrival metering fix delivery accuracy enables improved TRACON merging, with resulting airport throughput and delay distribution savings. Additionally, the smoother downstream operations require less TRACON front-loading,[2] enabling delay to be absorbed more efficiently in upstream ARTCC airspace. However, because of limits on TRACON arrival routes delay absorption, only limited delay is shifted out of the TRACON until the arrival metering fix accuracy is improved. Thus, this limits the Center/TRACON delay distribution benefits of EDX1 and EDX2 relative to the Passive Baseline. Likewise, throughput benefits are reduced under the Active Baseline due to the high baseline metering fix accuracy without EDX. It should be noted that the high cost of time, relative to fuel, has a significant impact. Airport throughput and departure direct routing are the only EDX mechanism to include time savings, which represents two-thirds of the benefit for these mechanisms.

The next largest EDX benefit occurs with separation assurance ATM interruptions, which were shown to save $3.6M annually. Related benefits from EDX1 and EDX2, assumed in the baseline, were not assessed. Finally, the FMS descent speed profile negotiation saved $1.1M annually.

In addition to these quantified benefits are EDX improvements to pilot and controller workload and safety. Overall safety is enhanced due to improved surveillance under EDX operations. Additionally, the accuracy of ATM DST advisories is improved, reducing the need for additional corrective interruptions and increasing controller confidence. For example, in early EDA testing, over two-thirds of the EDA clearances provided to controllers required no modification, being acceptable in both method (speed, heading, altitude) and magnitude [70]. EDX should further improve this acceptability. Indeed, the separation assurance ATM interruptions analysis showed the EDX trajectory prediction accuracy and intent improvement greatly reduced the number of missed or nuisance (false) conflict alerts, with a 25 and 7 percent reduction, respectively. Note that most of the false alerts improvement occurred due to the downlink of the next two waypoints (EDX5). However, the modeling method precluded assessing the impact of EDX5 on missed alerts.

Although these benefits may appear small, relative to those expected for a new ATM DST, it should be noted that implementation of EDX concepts requires only minor changes to existing or planned datalink, ATM DST, and aircraft FMS technologies, greatly reducing EDX costs. Also, due to the many assumptions, varying levels of analysis fidelity, and lack of detailed technical and operational assessment of assessments, these benefits estimates should be used as engineering estimates. These estimates should be validated and improved through further study,

[2] Current operations front-load the TRACON during rush periods, which entails pushing several minutes of the total flight delay into the TRACON (e.g. longer final approach flight segments) in order to address metering fix delivery and other flight uncertainties.

ongoing experimental results, and maturation of the EDX concept. Specific recommendations to improve the analyses are included in the final chapter of the report.

1. Airport Throughput Benefits

Air Traffic Management automation tools rely on accurate predictions of flight trajectories to derive terminal area arrival and departure sequences and schedules. In the en route environment, this scheduling process can be evaluated by the ability of ATM to consistently deliver flights to the arrival and departure metering fixes as scheduled, with minimal excess in-trail separation. Data exchange trajectory prediction enhancement results in increased DST schedule integrity, increased efficiency of controller clearances to meet the schedule and subsequent enhanced delivery accuracy, and provides a smoother traffic stream for downstream operations.

A key scheduling benefit of improved trajectory prediction is the ability to increase airport/airspace throughput as improved trajectory prediction allows controllers to tighten in-trail spacing at the same level of safety. Indeed, due to delay propagation during rush periods, small savings in individual aircraft pair separation leads to large decreases in delay. It should be noted that the, has a significant impact, despite a small average delay savings of less than one minute per rush arrival. Airport throughput is the only EDA mechanism to include time savings, which represents two-thirds of the benefit for this mechanism. Because of the high cost of time relative to fuel, implementing spacing buffer reduction can reduce time/delay leading to significant user benefits [7-9, 31]. Data exchange between the airspace user (either the flight crew or AOC) enables the DSTs to reduce excess spacing buffers and improve schedule integrity and schedule adherence; these lead to increased capacity and reduced delay.

Specifically, this benefit mechanism concerns the reduction in spacing gaps between aircraft on final approach, thereby producing a higher airport runway system throughput. EDX is expected to enable this mechanism by improving DST scheduling operations, which assist controllers in delivering aircraft to the Center/TRACON metering fixes in accordance with the DST meter fix crossing schedule. In references [11] the EDX benefits of reduced spacing buffers leading to improved runway throughput and airport capacity was estimated. Since then, field evaluations and additional analysis have lead to improved estimates of EDX trajectory prediction accuracy that were used to update the results of the previous studies

Analysis Process

The benefits methodology process employed in previous research [7-9, 31] and updated here, is described below. The sequence of analytical formulations and computer-based modelings follows the Figure 1 approach (and numbering) of the introduction summary section. The Trajectory Prediction Accuracy Model (2) uses baseline and EDA defined data parameter accuracies to calculate the expected statistical timing error in CTAS' prediction of when the aircraft will cross the meter fix (MF) and runway threshold waypoints. This MF timing error is then converted into excess spacing buffers, which would be imposed by air traffic controllers to limit separation minima violations. These aircraft spacings, defined for baseline and EDX cases, are then combined with airport daily traffic schedule in a runway system demand and capacity model (3). The resulting delay savings from the EDX cases, at 11 airports are then converted to user direct operating cost savings (time and fuel) and extrapolated to annual and NAS-wide levels (4). These model components are discussed in more depth with the analysis results in the next section. (It is again noted that a higher-fidelity IAT model has been developed to evaluate ATM scheduling DSTs. Use of this model to update the analysis based on using the limited

AIRNET model would improve the confidence and accuracy of the resulting EDX runway throughput benefit estimates.)

Study Cases

The analysis process is initiated by identifying the various candidate technologies, and their capabilities, that may be associated with EDX runway throughput benefits. The EDX cases evaluated under this benefit mechanism include EDX1 through EDX3 relative to both a Passive and Active Baseline. Each case provides an additional improvement upon the arrival trajectory prediction accuracy. The cases include both en route and TRACON modeling, although only the en route tools are enhanced with data exchange. All cases assume 100% FMS equipage and data exchange participation.

- **Passive Baseline** – En Route TMA with TRACON pFAST
- **Active Baseline** – En Route TMA/EDA with TRACON AFAST
- **EDX1 – Weather (wind & temperature)** Data Exchange
- **EDX2** – Weather, **Aircraft Weight, Thrust/Drag Coefficients** Data Exchange
- **EDX3 –** Weather, Weight, Thrust/Drag, **Arrival/Departure Speed Intent** Data Exchange

Trajectory Parameter Accuracies

Each baseline and EDX operational case is described in terms of values of statistical parameters which contribute to DST aircraft trajectory prediction accuracy. These parametric values, shown in Table 1.1 for each study case, represent stochastic distributions which quantitatively describes the accuracy of each contributing parameter. The parameters used in the model have been calibrated and adjusted to reflect the findings of recent CTAS prototype field tests. [20]

Trajectory Accuracy and Traffic Spacing Modeling

Air traffic controllers impose an intentional spacing buffer added to the minimum spacing between adjacent aircraft. This buffer serves in part to assure that separation minima are not violated because of trajectory uncertainties. Much of this excess spacing is generated because of uncertainty in the delivery of arrival aircraft at the inbound metering fixes. A schedule of aircraft crossing times at each fix is set by the CTAS-based ATM process according to a TRACON airspace and runway system utilization rate. However, deviations from the metering fix crossing schedule due to timing delivery inaccuracies require subsequent trajectory adjustments by the TRACON ATM operation to prevent violations of separation minima and, to the extent possible, eliminate extraneous gaps at downstream merge points and the runway threshold.

The reduction in trajectory uncertainty due to data exchange, relative to the baseline, would result in a reduction in the size of the excess spacing buffer needed to compensate for trajectory variances. The smaller buffer would reduce the spacing applied between successive aircraft as shown in Figure 1.1, thereby increasing the throughput of the runway system. The increased throughput would reduce delays experienced by aircraft when demand approaches or exceeds the capacity of the runway system. These reduced delays result in reduced fuel and time costs incurred by aircraft operators. Reduced delays also support the integrity of the airline schedule of connecting flights.

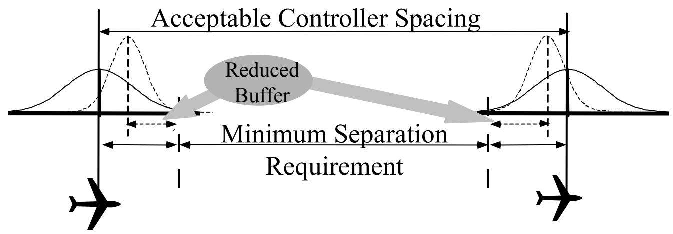


Figure 1.1 Reduced Excess Spacing with Improved Trajectory Prediction Accuracy

Table 1.1 Assumed Trajectory Accuracy Parameters

			Standard Deviation							
			Passive Baseline				Active Baseline			
Parameter	Units	Mean	BL	EDX1	EDX2	EDX3	BL	EDX1	EDX2	EDX3
Center										
Initial Weight	%	0	7.8	7.8	**5.6**	**5.6**	7.8	7.8	**5.6**	5.6
Aerodynamic Drag	%	0	5.9	5.9	**2.1**	**2.1**	5.9	5.9	**2.1**	2.1
TOD Placement	nm	0	20	20	20	20	0.25	0.25	0.25	0.25
Spd Adherence (CAS)	kt	0	15	15	15	**4**	4	4	4	**4**
X-Track Wander	nm	0	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Aircraft Nav. Bias	deg.	0	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Turn Dynamics	sec	0	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3
Wind Forecast	kt	0	12	**8.9**	8.9	8.9	12	**8.9**	8.9	8.9
Temp. Forecast	°C	0	1	**0.5**	0.5	0.5	1	**0.5**	0.5	0.5
Surveillance	kt	0	13.1	13.1	13.1	13.1	13.1	13.1	13.1	13.1
TRACON										
Final Advisory	sec	0	9.75	9.75	9.75	9.75	8.49	8.49	8.49	8.49
Turn variation	sec	35	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Deceleration	%	0.52	0.120	0.120	0.120	0.120	0.120	0.120	0.120	0.120
Descent rate	ft/min	1440	160	160	160	160	160	160	160	160
Speed adherence	kt	0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Wind forecast	kt	0	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Tracker	kt	0	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
AFAST Optimal Rwy Balancing/Sequencing	sec	2.3	No	No	No	No	Yes	Yes	Yes	Yes
Final Approach										
Outer Marker Speed	kt	0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Threshold Speed	kt	0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Headwind	kt	0	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
Decel delay time	sec	0	12	12	12	12	12	12	12	12

The accuracy with which trajectories can be predicted is estimated using computer simulation, closed-form analytical solutions, and a combination of the two, as appropriate, for each phase of flight. The original simulated trajectories, from arrival metering fix to runway threshold, are shown in Figure 1.2; these represent a typical set of approach paths specific to DFW. A more extensive discussion of the assumed parameter uncertainties and the trajectory accuracy modeling are included in Chapter 4. (Note that simulating the specific STAR routes could generate more accurate results and approach paths nominally used at each of the subject airports.)

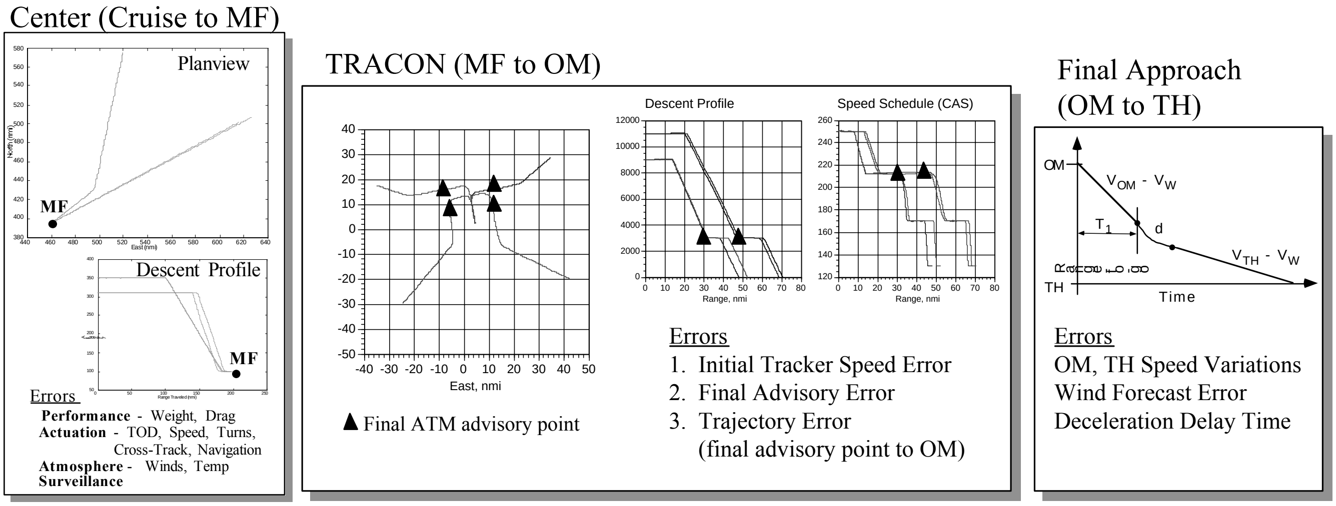


Figure 1.2 Arrival Trajectory Prediction Accuracy Simulation

The parameter accuracy distributions, defined for each operational case in Table 1.1, are inputs to the trajectory modeling process. Note that EDX only impacts the Center accuracy, since it is assumed in this analysis that only en route DSTs are modified to make use of the downlinked data. The outputs, shown in Table 1.2, are the arrival metering fix uncertainty (see Appendix B) and the resulting runway threshold excess spacing buffer contribution. Although only the Center spacing contribution improves under EDA, the TRACON and Final Approach buffer contributions are also provided to gauge of the relative importance of the various contributions. The contributions are combined using Equation (1.1), with the Center contribution to the runway buffer (μ_{OM}) derived from the metering fix delivery accuracy per Reference [31]:

$$\textit{Runway Excess Spacing Buffer} = \mu_{MS} + \sqrt{\sigma_{OM}^2 + \sigma_{FA}^2} \tag{1.1}$$

The runway spacing buffers, using Equation (1.1) with the Table 1.2 contributions are given in matrix form in Table 1.3, as a function of the various leading/trailing weight-dependent aircraft minimum spacing combinations. Note that the Center model metering fix delivery uncertainty values (assuming a 15-minute descent) were calibrated to match findings of TMA [20] and EDA [22] prototype operations at DFW as discussed in Appendix B.

Table 1.4 gives the fleet-weighted equivalent runway buffers estimated for each study case and each of the subject airports. Note that EDX1 shows limited improvement relative to the Passive Baseline and EDX3 shows no improvement relative to the Active Baseline. The buffers of Tables 1.3 and 1.4 are applied as additions to the FAA runway spacing minima of Table 1.5. Note that EDX1 in the Passive Baseline case shows negligible improve due to the limited impact of better weather accuracy when other trajectory errors remain large. Likewise for EDX3 in the Active Baseline case, which shows no improvement because the arrival speed intent improvement is realized with the implementation of EDA, part of the Active Baseline.

Table 1.2 Assumed Arrival Trajectory Prediction Accuracy

	Units	Passive CTAS Baseline BL	Passive CTAS Baseline EDX1	Passive CTAS Baseline EDX2	Passive CTAS Baseline EDX3	Active CTAS Baseline BL	Active CTAS Baseline EDX1	Active CTAS Baseline EDX2	Active CTAS Baseline EDX3
Center									
MF uncertainty (σ_{MF})	Sec	**86.1**	85.6	85.2	82.5	**17.9**	15.6	12.8	12.8
TH Excess Spacing Contribution (μ_{MS})	Sec	0.72	0.72	0.70	0.65	0.07	0.06	0.05	0.05
TRACON									
OM pairwise spacing (σ_{OM})	Sec	22.53	22.53	22.53	22.53	21.48	21.48	21.48	21.48
Final Approach									
Final Approach TH Equivalent Buffer Contribution (DFW) (σ_{FA})	Sec	11.31	11.31	11.31	11.31	11.26	11.26	11.26	11.26

Note: Bold values calibrated to approximate 90 and 15-20 sec (1-sigma) MF delivery error of TMA [20] and EDA [22] prototype field tests.

Table 1.3 Arrival Runway Threshold Excess Spacing Buffer (sec)

	Passive Baseline			EDX1			EDX2			EDX3		
	Trailing Aircraft			Trailing Aircraft			Trailing Aircraft			Trailing Aircraft		
Lead a/c:	Small	Large	Heavy	Small	Large	Heavy	Small	Large	Heavy	Small	Large	Heavy
Small	25.91	25.54	25.28	25.91	25.54	25.28	25.88	25.52	25.25	25.83	25.47	25.20
Large	27.27	25.49	25.04	27.27	25.49	25.04	27.24	25.46	25.01	27.20	25.42	24.96
Heavy	28.87	27.38	25.55	28.87	27.38	25.55	28.85	27.35	25.52	28.80	27.31	25.48

	Active Baseline			EDX1			EDX2 and EDX3		
	Trailing Aircraft			Trailing Aircraft			Trailing Aircraft		
Lead a/c:	Small	Large	Heavy	Small	Large	Heavy	Small	Large	Heavy
Small	22.11	21.74	21.46	22.10	21.73	21.46	22.09	21.72	21.45
Large	23.50	21.68	21.22	23.49	21.67	21.21	23.48	21.66	21.20
Heavy	25.14	23.61	21.73	25.13	23.60	21.72	25.12	23.59	21.71

Table 1.4 Equivalent Threshold Excess Spacing Buffers

	Equivalent Threshold Excess Spacing Buffer (sec)					
	Passive Baseline			Active Baseline		
Airport	BL/EDX1	EDX2	EDX3	BL	EDX1	EDX2/3
Atlanta (ATL)	25.79	25.76	25.71	21.98	21.97	21.96
Nashville (BNA)	26.02	26.00	25.95	22.23	22.22	22.21
Boston (BOS)	26.11	26.09	26.04	22.32	22.31	22.30
Baltimore (BWI)	25.89	25.86	25.81	22.09	22.08	22.07
Charlotte (CLT)	25.96	25.93	25.89	22.16	22.15	22.14
Cincinnati (CVG)	25.73	25.71	25.66	21.93	21.92	21.91
Washington National (DCA)	25.93	25.90	25.85	22.13	22.12	22.11
Denver (DEN)	26.01	25.98	25.94	22.21	22.20	22.19
Dallas – Ft. Worth (DFW)	25.77	25.74	25.69	21.97	21.96	21.95
Detroit (DTW)	26.04	26.02	25.97	22.25	22.24	22.23
Newark (EWR)	25.85	25.83	25.78	22.05	22.04	22.03
Washington Dulles (IAD)	26.19	26.17	26.12	22.40	22.39	22.38
Houston – Intercontinental (IAH)	25.74	25.72	25.67	21.94	21.93	21.92
N.Y. Kennedy (JFK)	26.00	25.98	25.93	22.20	22.19	22.18
Las Vegas (LAS)	26.06	26.03	25.98	22.26	22.25	22.24
Los Angeles (LAX)	26.19	26.16	26.12	22.40	22.39	22.38
N.Y. LaGuardia (LGA)	25.85	25.83	25.78	22.05	22.04	22.03
Orlando (MCO)	26.07	26.04	26.00	22.27	22.26	22.25
Memphis (MEM)	26.07	26.04	26.00	22.27	22.27	22.26
Miami (MIA)	26.10	26.08	26.03	22.31	22.30	22.29
Minneapolis (MSP)	22.35	26.12	26.07	22.35	22.34	22.33
Chicago O'Hare (ORD)	25.79	25.77	25.72	21.99	21.98	21.97
Philadelphia (PHL)	25.99	25.97	25.92	22.20	22.19	22.18
Phoenix (PHX)	26.07	26.04	25.99	22.27	22.26	22.25
Pittsburgh (PIT)	26.00	25.98	25.93	22.21	22.20	22.19
Seattle (SEA)	26.02	26.00	25.95	22.23	22.22	22.21
San Francisco (SFO)	26.06	26.04	25.99	22.26	22.25	22.24
Salt Lake City (SLC)	26.03	26.00	25.95	22.23	22.22	22.21
St. Louis (STL)	25.86	25.83	25.79	22.06	22.05	22.04

Table 1.5 FAA Minimum Separation

	FAA Minima (nm/sec)		
	Trailing Aircraft		
Lead a/c:	Small	Large	Small
Small	2.5/75	2.5/72	2.5/67
Large	4.0/120	2.5/72	2.5/67
Heavy	6.0/180	5.0/144	4.0/107

Runway System Demand and Capacity Model

A computer simulation model is used to evaluate airport throughput and determine traffic delay using the excess spacing buffer data and minimum separation requirements as input. Each of the 29 study airports was modeled over a single typical daily traffic schedule. The model incorporates data describing time-varying daily schedules for various types of commercial, general aviation and military aircraft and detailed configurations of the major domestic airports for instrument flight rules (IFR) and visual flight rules (VFR). Runway spacing parameters describing separation procedures for the IFR and VFR runway configurations at each of the 29 airports are adjusted to enable comparison of the baseline and EDX scenarios. The DFW modeled runway configurations is shown in Figure 1.3, with other airport configurations described in Appendix C.

Although the daily traffic schedule used in this analysis differs from that employed in the other benefits evaluations, cross-comparable results are achieved by extrapolating the daily per operation savings results to annual airport activity levels consistent with the other studies.

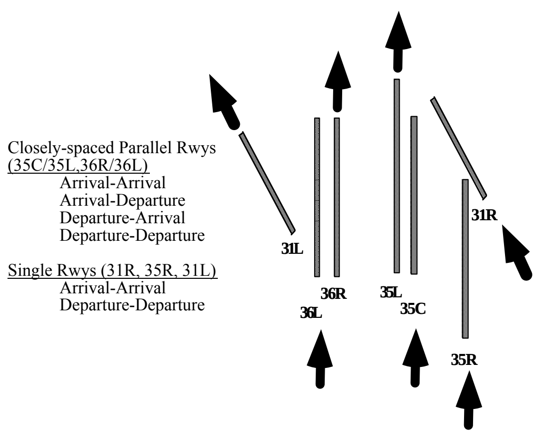


Figure 1.3 Average Airport Delay as a Function of Runway Excess Spacing

The modeling of each airport resulted in delays of four categories as a function of the input runway spacing buffer, as shown in Figure 1.4. The four delay categories include:

- Instrument Flight Rules (IFR) Arrival Delay
- Visual Flight Rules (VFR) Arrival Delay
- IFR Departure Delay
- VFR Departure Delay

IFR delays were averaged over a morning IFR period from 7-10 am, weighted by the historical persistence of IMC at each airport. VFR delays reflect the average delay over the remaining VFR period. Figure 1.4 shows how delays (y-axis) decline at each airport with a reduction in the runway threshold excess spacing buffer (x-axis). Using the Figure 1.4 simulation results and the equivalent spacing buffers of Table 1.4, delay estimates in each category were identified for the baseline and EDX systems. Assuming an even split of arrivals and departures and historical share of instrument meteorological conditions (IMC) (see Appendix C), the four delay categories are combined and summarized, as shown in Table 1.6.

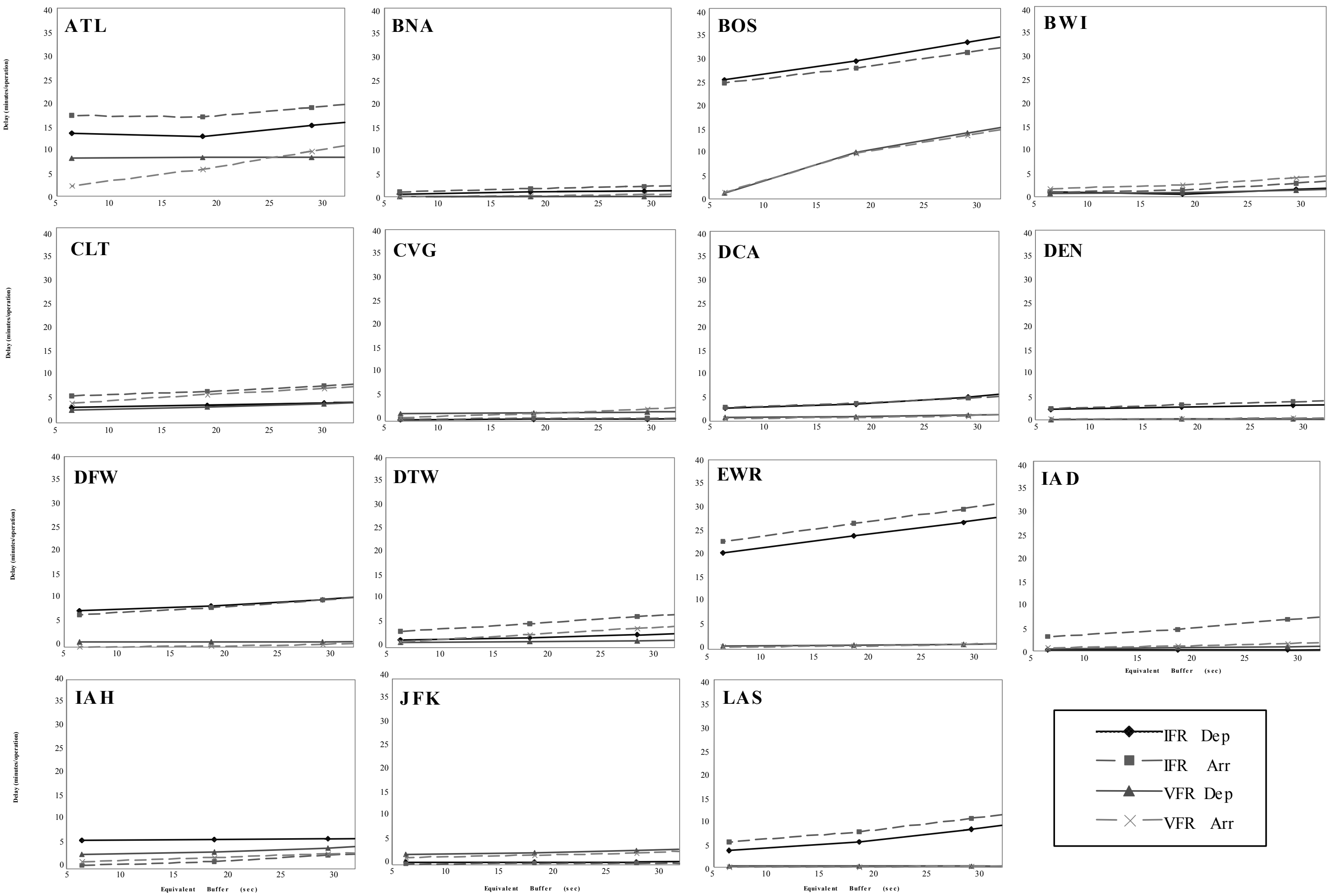


Figure 1.4a Airport Delay as a Function of Runway Excess Spacing Buffer

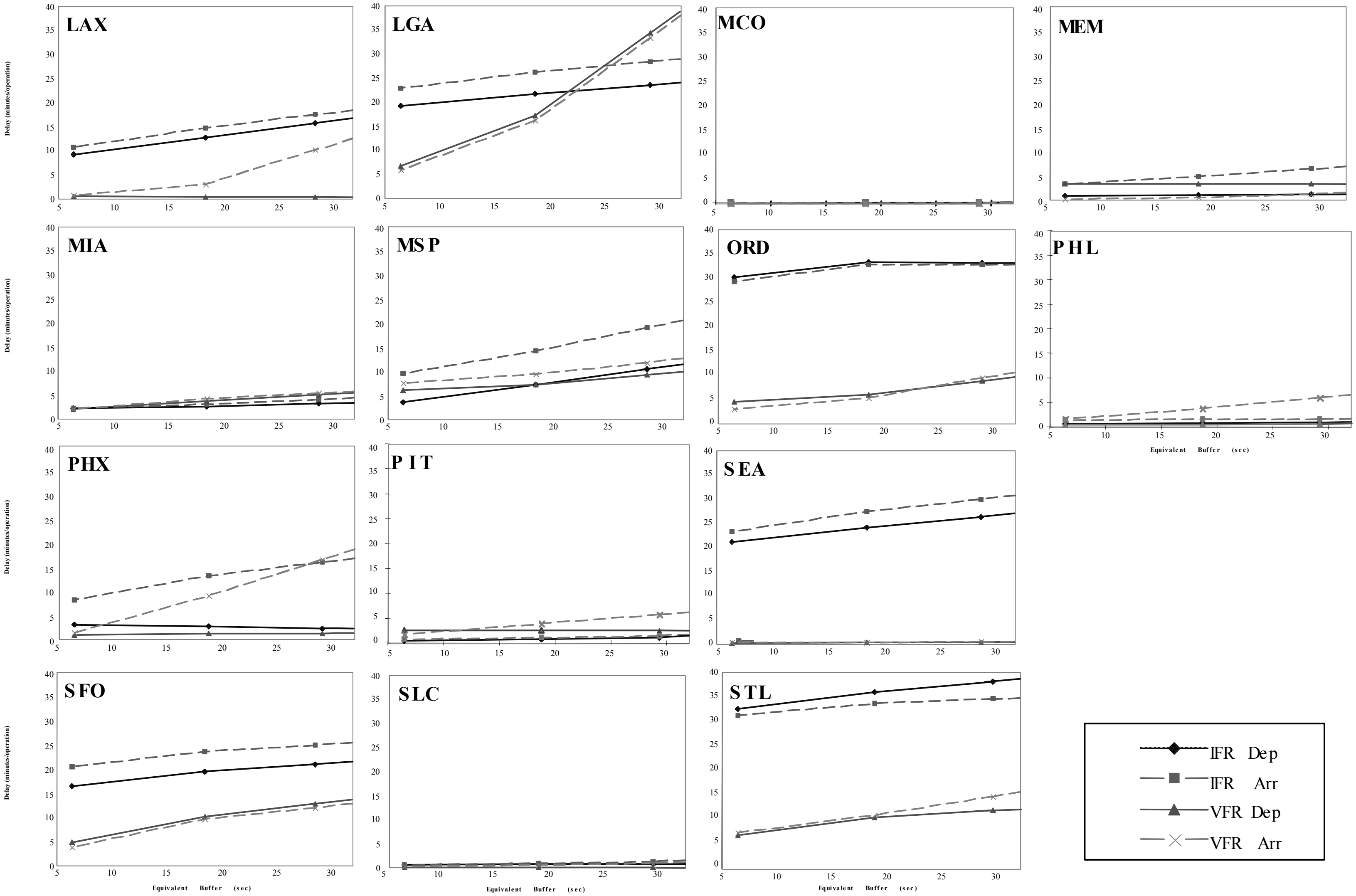


Figure 1.4b Airport Delay as a Function of Runway Excess Spacing Buffer (cont'd)

Table 1.6 EDX Delay Savings

	Average Delay Savings (seconds/operation)			
	Passive Baseline		Active Baseline	
Airport	EDX2	EDX3	EDX1	EDX2/3
Atlanta (ATL)	0.27	0.80	0.11	0.22
Nashville (BNA)	0.02	0.05	0.01	0.01
Boston (BOS)	0.55	1.63	0.21	0.44
Baltimore (BWI)	0.15	0.44	0.06	0.12
Charlotte (CLT)	0.13	0.39	0.05	0.11
Cincinnati (CVG)	0.06	0.17	0.02	0.05
Washington National (DCA)	0.06	0.18	0.02	0.05
Denver (DEN)	0.02	0.05	0.01	0.01
Dallas – Ft. Worth (DFW)	0.04	0.12	0.02	0.03
Detroit (DTW)	0.12	0.37	0.05	0.10
Newark (EWR)	0.09	0.27	0.04	0.07
Washington Dulles (IAD)	0.06	0.17	0.02	0.05
Houston – Intercontinental (IAH)	0.11	0.32	0.04	0.09
N.Y. Kennedy (JFK)	0.06	0.18	0.02	0.05
Las Vegas (LAS)	0.01	0.02	0.00	0.00
Los Angeles (LAX)	0.51	1.50	0.19	0.40
N.Y. LaGuardia (LGA)	2.06	6.10	0.83	1.67
Orlando (MCO)	0.00	0.00	0.00	0.00
Memphis (MEM)	0.06	0.18	0.02	0.05
Miami (MIA)	0.17	0.50	0.07	0.14
Minneapolis (MSP)	0.35	1.03	0.13	0.28
Chicago O'Hare (ORD)	0.40	1.20	0.16	0.33
Philadelphia (PHL)	0.14	0.41	0.06	0.11
Phoenix (PHX)	0.53	1.57	0.21	0.43
Pittsburgh (PIT)	0.11	0.32	0.04	0.09
Seattle (SEA)	0.06	0.18	0.02	0.05
San Francisco (SFO)	0.35	1.03	0.13	0.28
Salt Lake City (SLC)	0.03	0.07	0.01	0.02
St. Louis (STL)	0.33	0.99	0.13	0.27

Economic Analysis

The daily traffic delay data are extrapolated to annual cost savings by airport using detailed aircraft operating costs and airport traffic and meteorological factors. Calculation of potential annual delay cost savings follows Equation (1.2):

$$\textit{Annual Savings} = (\textit{Annual Ops}) \times (\textit{Average Delay Savings per Op}) \times (\textit{Delay Cost Rate}) \qquad (1.2)$$

where: *Annual Ops* = Annual Airport operations (IMC & VMC) (Appendix C)
Average Delay Savings Per Op = Average delay savings per airport operation (min) (Table 1.5)
Delay Cost Rate = Fleet-weighted flight cost ($/min) (departure & arrival rates) (Appendix C)

This formulation is evaluated for four operation types:

IFR Arrivals & Departures - Accounting for historic airport-specific persistence and occurrence of IMC.
VFR Arrivals & Departures - Accounting for historic airport-specific occurrence of VMC.

This general formula is followed for each EDX enhancement, relative to the two baseline cases at each airport. Equation (1.2) delay data, for each of the 4 operation types, are found in Table 1.6 and aircraft cost rates and annual traffic levels are identified in Appendix B. Aircraft direct operating cost rates including crew, maintenance, oil, and fuel costs and are evaluated as an airport fleet-wide average. Departure fuel costs are less as departure delays are assumed to be held on the ground, rather than the airborne holding of arrivals. Per Operation delay savings for the eight airports not simulated was assumed equivalent to the closest simulated airport, based on FAA 1996 delay data [35], also included in Appendix C.

Table 1.6 and Figure 1.7 identify the 1996 estimated annual cost savings (in 1998 dollars) due to the EDX study cases for the 37 NAS-wide airports, assuming 100% aircraft data exchange participation and FMS equipage. The Passive Baseline EDX cases result in significantly more benefit. Two EDX cases showed no benefit: wind/temperature downlink (EDX1) under the Passive Baseline, due to negligible impact on metering fix delivery accuracy, and speed intent downlink (EDX3) under the Active Baseline, which assumes EDA, part of the Active Baseline, has already made this improvement for arrivals. The capacity-constrained large hub airports of LGA, LAX, ORD, ATL, and PHX accrued the most significant benefit estimates. It is again noted that the Passive Baseline benefits may be optimistic. Further analysis to better understand the impact of data exchange on the Passive Baseline advisories and ultimate system performance is recommended.

Results Summary

This chapter evaluated EDX airport throughput benefits. Reduced runway threshold crossing separations between consecutive pairs of landing aircraft (in excess of minimums) are expected from EDX as a result of improved arrival metering fix delivery accuracy. The reduced variance in arrival metering fix crossing times leads to reduced runway gaps with associated airport throughput increases and aircraft delay and delay propagation reduction, especially during rush periods. EDX enhancements to the Passive Baseline saved the most. EDX2 and EDX3 Passive Baseline operations saved an average 0.70 seconds of delay or $0.26 per operation (time and fuel), for a total NAS-wide deployment at 37-airports of 49.5 hours and $4.8M annually. EDX1 and EDX2 Active Baseline operations saved 0.19 seconds of delay or $0.07 per operation, for a total NAS-wide deployment at 37-airports of 13.4 hours and $1.3M annually.

These benefits reflect a reduction in the average runway threshold excess spacing buffer. A rough indication of the benefits to DST (EDA, TMA, and pFAST) throughput can be made by noting the airport delay savings in Figure 1.4. These are approximately 1-2 second TMA buffer improvement, 4 second pFAST improvement, 1 second EDA improvement, and this study's 0.08/0.02 second Passive/Active Baseline buffer improvement (Table 1.4).

It should also be noted that this analysis, an update of previous studies, was limited by the use of a runway demand and capacity modeling tool (AIRNET) which does not account for airspace constraints and subtleties of arrival scheduling embedded in proposed ATM DSTs. To address these limitations, Seagull has initiated development of a higher fidelity model, the Integrated Air Traffic (IAT) Model, which has been used in recent benefits assessments for TMA and EDA [30]. Additionally, there is some concern regarding the underlying schedule used to model LGA. Because of the high demand at LGA, delays are unable to dissipate, and they build-up without break over the full day. As a result, any improvement to LGA runway separation leads to significant savings. It is recommended that the IAT model be applied to refine these airport throughput benefits and the LGA flight schedule be updated to reflect existing activity.

Table 1.7 EDX Airport Throughput Benefits

Airport	Annual Airport Ops (000s)	Share of IMC	"Equivalent" Airport	Annual Cost Savings ($000s, 1998) Passive Baseline EDX2	EDX3	Active Baseline EDX1	EDX2/3
Atlanta (ATL)	773	14.2%		120.78	357.89	48.91	98.21
Bradley (BDL)	161	14.6%	DEN	1.22	3.61	0.48	0.98
Nashville (BNA)	226	9.5%		1.20	3.56	0.49	0.98
Boston (BOS)	463	15.6%		94.57	280.22	36.77	75.37
Baltimore (BWI)	270	12.4%		15.49	45.90	6.22	12.55
Cleveland (CLE)	291	15.6%	SEA	7.55	22.37	2.97	6.05
Charlotte (CLT)	457	12.5%		21.94	65.01	8.83	17.79
Cincinnati (CVG)	394	15.0%		9.24	27.38	3.75	7.52
Washington National (DCA)	310	10.7%		7.44	22.05	2.97	6.01
Denver (DEN)	454	6.0%		3.85	11.40	1.52	3.09
Dallas – Ft. Worth (DFW)	870	8.4%		17.15	50.81	6.94	13.94
Detroit (DTW)	531	16.6%		32.97	97.70	12.84	26.30
Newark (EWR)	443	16.6%		19.41	57.51	7.80	15.72
Ft. Lauderdale (FLL)	236	3.0%	DEN	1.40	4.15	0.55	1.12
Houston Hobby (HOU)	252	13.5%	SLC	2.56	7.58	1.01	2.05
Washington Dulles (IAD)	330	11.7%		6.45	19.12	2.47	5.10
Houston – Intercontinental (IAH)	392	12.7%		18.16	53.80	7.38	14.79
N.Y. Kennedy (JFK)	361	15.0%		14.90	44.15	5.83	11.91
Las Vegas (LAS)	480	0.3%		1.20	3.55	0.47	0.96
Los Angeles (LAX)	764	22.2%		213.75	633.38	80.21	167.46
N.Y. LaGuardia (LGA)	343	16.4%		311.63	923.46	125.40	252.59
Orlando (MCO)	342	5.9%		0.12	0.36	0.05	0.10
Chicago Midway (MDW)	254	15.1%	MIA	15.85	46.96	6.12	12.59
Memphis (MEM)	364	9.2%		11.19	33.17	4.36	8.93
Miami (MIA)	546	2.3%		41.54	123.11	16.05	33.00
Minneapolis (MSP)	484	11.6%		72.02	213.41	27.52	56.92
Oakland (OAK)	516	14.4%	MEM	10.10	29.92	3.93	8.05
Chicago O'Hare (ORD)	909	16.1%		192.40	570.12	77.79	156.32
Portland (PDX)	306	10.2%	DEN	2.26	6.69	0.89	1.81
Philadelphia (PHL)	406	15.0%		24.25	71.87	9.65	19.55
Phoenix (PHX)	544	0.5%		127.25	377.09	50.03	101.97
Pittsburgh (PIT)	447	24.6%		19.39	57.46	7.76	15.67
San Diego (SAN)	244	12.6%	SLC	3.39	10.06	1.34	2.72
Seattle (SEA)	398	14.9%		10.81	32.04	4.25	8.66
San Francisco (SFO)	442	12.5%		79.80	236.46	30.94	63.51
Salt Lake City (SLC)	374	5.6%		4.18	12.40	1.65	3.36
St. Louis (STL)	517	11.5%		76.13	225.60	30.89	61.96
37-Airport Total	430	---	---	1,614	4,781	637	1,296

Note: Airports not simulated assumed the delays of an "Equivalent" simulated airport, based on FAA ACE Delay data [35] in Appendix C.

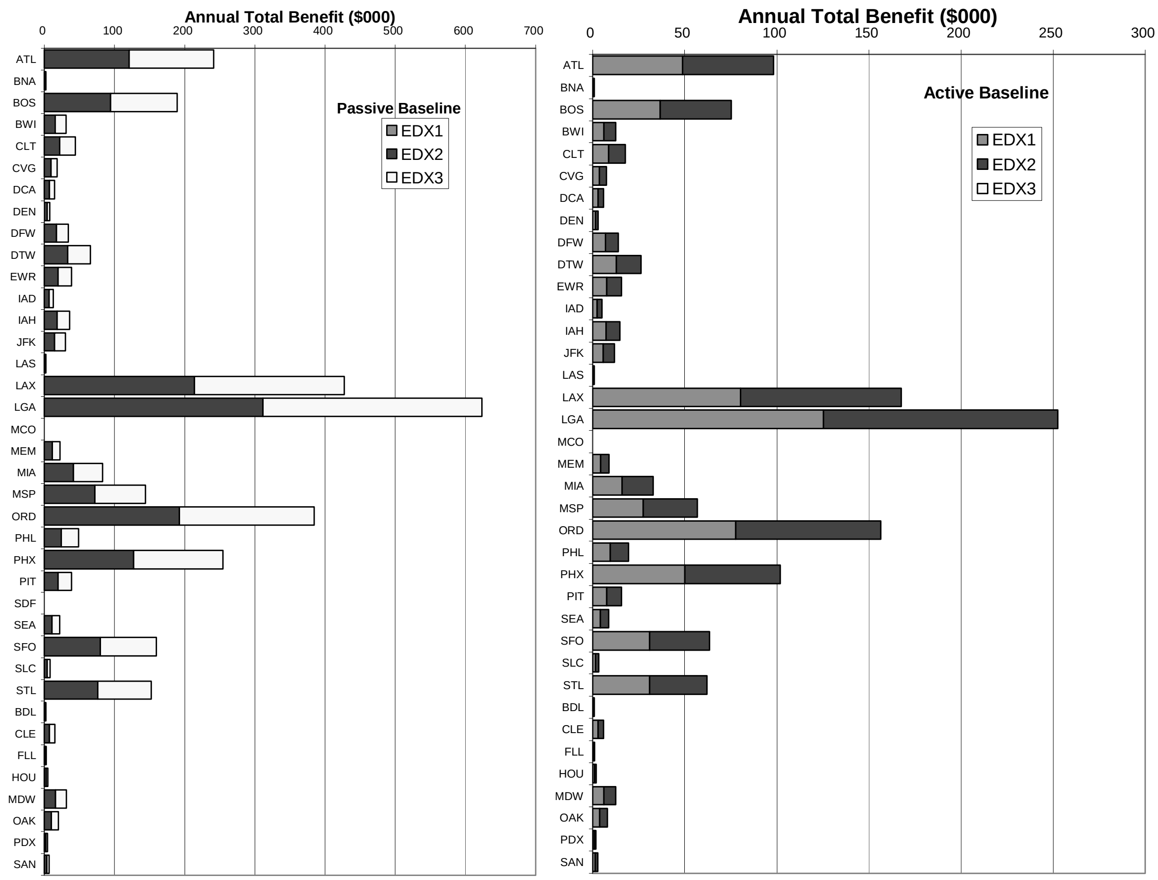


Figure 1.5 EDX Airport Throughput Benefits

2. Center/TRACON Delay Distribution Benefits

During busy periods, aircraft arrivals are metered to meet airport capacity restrictions. Controllers distribute overall arrival aircraft delay between Center and TRACON airspace during busy traffic periods. This allocation process performs a trade-off between the advantage of absorbing delay at upstream in the Center airspace, where fuel-efficiency is greater, versus the advantage of packing more aircraft in the terminal airspace to ensure that aircraft are continually available to use the runway system. The TRACON delay allows controllers flexibility to absorb variability in arrival-metering fix crossing time. Excess allocation of delay to the Center airspace degrades runway system utilization. As trajectory prediction and control accuracy are improved, less delay is needed in the TRACON airspace to maintain high runway system throughput. An increase in the proportion of total delay taken in the Center provides cost savings due to the ability to absorb delay more efficiently in Center airspace.

Thus, separate from runway throughput impacts of the previous chapter, improved arrival metering fix (MF) timing accuracy with EDX can also allow ATM to improve how the aforementioned metering delays are absorbed. With improved MF arrival stream delivery timing, less TRACON delay or front-loading is needed to absorb MF crossing variations, while maintaining high runway system throughput. As a result, extra TRACON time currently imposed on peak-period arrivals for this purpose can be shifted upstream to ARTCC airspace for more efficient absorption (fuel savings). The estimated fuel savings contributions for each of the EDX cases were tabulated at 3 airports, and then extrapolated to annual and NAS-wide levels.

Analysis Process

The benefits assessment methodology process employed in previous research [30] and updated here for EDX, is described below. The sequence of analytical formulations and computer-based modelings follows the Figure 1 approach (and numbering) of the introduction summary section. The Trajectory Prediction Accuracy Model (2) uses baseline and EDA defined data parameter accuracies to calculate the expected timing error in CTAS' prediction of when the aircraft will cross the meter fix (MF). This timing error as well as airport-specific arrival routes, arrival procedures, and arrival rush schedules (3), are used to identify the optimum level of TRACON delay. A reduction in the TRACON delay setting relative to baseline operations indicates the amount of delay that can be shifted upstream and absorbed in the more fuel-efficient ARTCC airspace. The resulting delay savings from the EDX case, at 3 airports (ATL, DFW, and LAX) are then converted to user direct operating cost savings (fuel) and extrapolated to annual and NAS-wide levels (4). These model components are discussed in more depth with the analysis results in the following sections.

Study Cases

The analysis process is initiated by identifying the various candidate technologies, and their capabilities, that may be associated with EDX Center/TRACON Delay Distribution benefits. The EDX cases evaluated under this benefit mechanism include EDX1 through EDX4 relative to both a Passive and Active Baseline. Each case improves upon the arrival metering fix delivery accuracy or nominal TRACON flight time (EDX4). All cases assume 100% FMS equipage and data exchange participation.

- **Passive Baseline** – TMA
- **Active Baseline** – TMA/EDA
- **EDX1 – Weather (wind & temperature)** Data Exchange
- **EDX2** – Weather, **Aircraft Weight, Thrust/Drag Coefficients** Data Exchange
- **EDX3** – Weather, Weight, Thrust/Drag, **Arrival/Departure Speed Intent** Data Exchange
- **EDX4** – Weather, Weight, Thrust/Drag, Speed Intent, **Threshold Crossing Speed Intent** Data Exchange

Delay Distribution

CTAS includes a delay distribution function, which allocates aircraft delay between Center and TRACON airspace during busy traffic periods. As discussed above, the allocation process is designed to achieve an optimum balance between fuel burn savings and runway system throughput. CTAS TMA and EDA, allow for this optimal distribution of delay between Center and TRACON airspace through a TRACON delay setting parameter. During rush periods, the parameter is increased to allow TRACON the controllability to fully utilize runway system throughput, at a fuel penalty of taking some of the delay in the TRACON airspace. As arrival fix crossing accuracy or predicted TRACON flight time improves, a lower TRACON delay setting is necessary to maintain runway system throughput, leading to associated fuel burn savings. Figure 2.1 shows the fuel burn penalty (ΔFuel) and runway utilization cost of increasing the TRACON delay setting parameter.

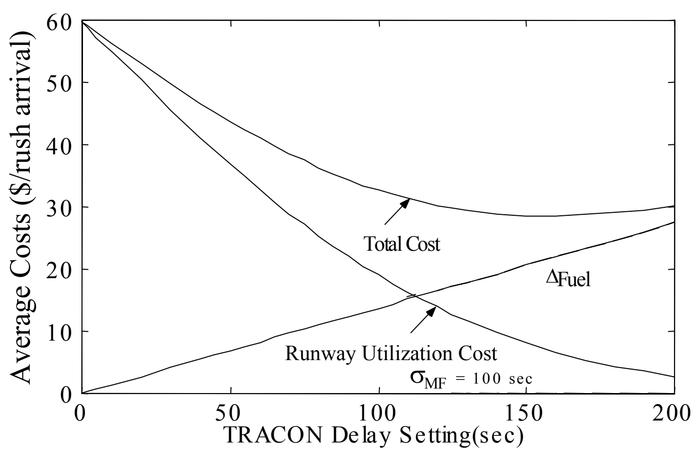


Figure 2.1 Runway Utilization and Fuel Burn Penalty Costs Vary with TRACON Delay Setting

Runway utilization costs reflect the delay impact of arrivals unable to meet their landing slot, despite the TRACON Delay Setting, as a result of arrival fix delivery variation. Previous research has analytically derived Equation 2.1 to calculate the optimum TRACON Delay Setting as a function of arrival fix delivery accuracy (σ_{MF}), fuel burn cost rates in the TRACON and Center (C_{FT}, C_{FC}), time costs, rush size (N), and a calibration factor (k_{Slot}). Equation (2.2) gives the EDX TRACON Delay Setting fuel burn savings for a flight relative to the Passive Baseline system. These savings would be zero, if the optimum setting exceeds the maximum setting, based on the controllability window of each TRACON arrival route at each airport.

$$\left. TRACON\ Delay\ Setting \right|_{OPT} = \sigma \sqrt{-2 \ln\left[\frac{\sqrt{8}\sigma(C_{FT} - C_{FC})}{(N+1)k_{Slot}(C_T + C_{FT})}\right]} \tag{2.1}$$

$$FuelSavings = (C_{FT}\text{-}C_{FC})\left(\left. TRACON\ Delay\ Setting \right|_{BL} - \left. TRACON\ Delay\ Setting \right|_{EDX} \right) \tag{2.2}$$

Although the EDX4 case does not impact the metering fix (MF) delivery accuracy, it improves the accuracy in predicting the TRACON time-to-fly and thus has the same impact of requiring less TRACON delay or front-loading to account for flight variability. Its TRACON delay setting estimation does not use Equations (2.1-2.2) and is discussed separately later.

Figure 2.2 illustrates how the optimal TRACON Delay setting (y-axis) declines with improved arrival metering fix delivery accuracy (x-axis). Note that the maximum delay absorption capability of a route (typically 100-300 seconds) may require a setting below optimal when the MF delivery error is large (shaded area of figure). Pre-TMA, TMA, and EDA MF delivery accuracies are shown for reference. Note that only small Center/ TRACON delay distribution benefits would be expected under TMA, since despite the large improvement in delivery accuracy, the TRACON delay setting did not change much. More benefits would be expected with post-TMA improvements.

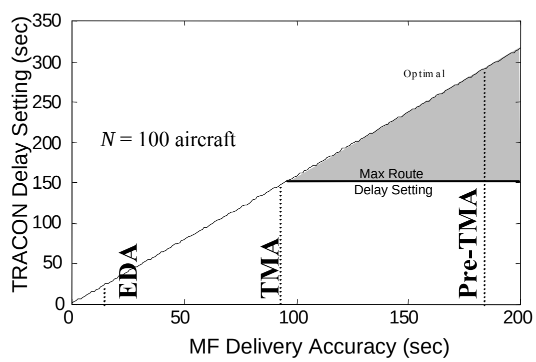


Figure 2.2 Optimal TRACON Delay Setting as a Function of Arrival Metering Fix Delivery Error

Equation Parameters

Equations (2.1-2.2) require case-specific metering fix delivery accuracy values (σ_{MF}). These values were obtained using the Trajectory and Traffic Spacing Model and case-specific values discussed in Chapter 1, Airport Throughput Benefits and discussed in Appendix B. The resulting MF arrival trajectory accuracies are repeated in Table 2.1.

Table 2.1 Assumed Arrival Trajectory Accuracy

	Units	Passive BL	EDX1	EDX2	EDX3	EDX4	Active BL	EDX1	EDX2	EDX3	EDX4
MF uncertainty (σ_{MF})	Sec	**86.1**	85.6	85.2	82.5	82.5	**17.9**	15.6	12.8	12.8	12.8

Note: Bold values calibrated to approximate 90 & 15-20 sec (1-sigma) MF delivery error of TMA [20] & EDA [22] prototype field tests.

Airport-specific parameters that apply to all study cases were identified through evaluation of the airport TRACON procedures and typical traffic operations. The maximum delay that could be absorbed in each TRACON route category was identified based on ATM facility-provided data [32] as well as geographic airspace and adjacent operations limitations, per discussions with each facility. Straight-in approaches in general have a smaller controllability window (i.e., less room to maneuver) and thus a lower maximum TRACON Delay Setting than the longer downwind-turn-to-base approaches. Additionally at LAX, two arrival fixes are often used to hold primarily non-jet aircraft for up to several minutes to fill holes on final approach, increasing their delay absorption capability.

Additionally, evaluation of a typical day's ETMS-based traffic operations at each of these facilities [33] was used to identify and characterize the arrival rushes at each facility. The assumed attributes are shown in Table 2.2

Table 2.2 ATL, DFW, LAX Assumed Airport Rush Operations

	Approach Procedure	**Max TRACON Delay** (sec)	**Airport Arrival Rushes** Start Time, Duration, Operations									
			Rush 1	Rush 2	Rush 3	Rush 4	Rush 5	Rush 6	Rush 7	Rush 8	Rush 9	Rush 10
ATL	Straight-In Downwind	150 300	07:20 33 min 40	08:43 51 min 62	10:38 55 min 64	12:14 63 min 79	14:10 67 min 77	15:41 94 min 116	17:35 79 min 99	19:36 89 min 109	21:47 55 min 63	
DFW	Straight-In Downwind	180 360	06:48 13 min 17	08:19 24 min 27	09:41 25 min 35	11:34 46 min 78	13:11 26 min 47	14:28 47 min 75	15:54 31 min 53	17:34 52 min 85	18:48 63 min 107	20:26 53 min 64
LAX	Straight-In Downwind PropHolding	100 300 360	09:17 29 min 31	10:40 102 min 122	13:53 71in 80	16:50 71 min 83	18:45 193 min 216					

Note: LAX Prop Holding Fixes are DARTS and SLI

The cost parameter values used in Equations (2.1-2.2) are shown in Table 2.3. Airport-specific costs of time and fuel (Center and TRACON) were weighted by the average airport fleet mix. Note the key assumption that TRACON fuelburn is 1.5 times ARTCC fuelburn rate. This may be optimistic and representative of costs under optimal conditions. In fact under current operations, rush arrival flights are typically delayed in the ARTCC with vectoring, which does not fully leverage more fuel-efficient speed control methods for delay absorption. Thus, the Center/TRACON fuelburn rate assumption may be more representative of the efficient EDA en route metering delay strategies assumed in the Active Baseline.

Table 2.3 Fleet-Weighted Time and Fuel Costs

	Airport Cost Rates ($/min		
Cost Type	ATL	DFW	LAX
Time	$20.63	$17.78	$18.01
Fuel – ARTCC	$10.89	$9.19	$9.51
Fuel – TRACON	$16.34	$13.78	$14.27

TRACON Delay Settings

In the passive ATM case, TMA sets the TRACON time-to-fly during rushes to include the minimum TRACON to MF time-to-fly plus the TRACON delay setting. Since the MF delivery accuracy in today's operations is typically quite large, the maximum TRACON delay setting is used. This has the effect of maximizing runway system utilization, at the expense of less fuel-efficient trajectories. As the MF delivery accuracy improves, this delay can be shifted to more fuel-efficient ARTCC airspace. The TRACON delay settings calculated for each baseline and EDX scenario are now discussed:

Baseline and EDX1-EDX3 TRACON Delay Settings

For each airport's rush/approach categories, optimum TRACON delay settings are defined from Equation (2.1) for the each case, with the parameter values of Tables 2.1 through 2.3. The optimal setting is then compared with the maximum settings defined in Table 2.2. These tables also show the operations using each approach route (e.g. straight-in, downwind) during the identified rushes. The DFW calculations of fuel savings per arrival and per rush are shown in Table 2.4a and 2.4b for the Passive and Active Baseline respectively. Note that because the optimal setting is the same regardless of approach, the same savings will occur for both approaches if not restricted by the maximum setting. This restriction primarily occurs at the lower MF delivery accuracies of the passive Baseline cases.

EDX4 TRACON Delay Setting

The aircraft downlink of intended threshold crossing speed in the EDX4 scenario, is expected to reduce the TRACON Delay Setting, leading to higher arrival fuel efficiency. Although the ability to meet the TMA schedule (σ_{MF}) is not expected to change significantly under EDX4, the underlying TMA schedule will be based on an improved CTAS prediction of the TRACON flight times, as shown in Figure 2.3. As a result, less TRACON delay or front-loading will be needed in the sequencing and merging of flights to the runway threshold. The current level of safety can be maintained by retaining a buffer proportional to the predicted flight time variation. We have assumed a 2σ buffer, encompassing all but 2.5 percent of the predicted flight times, represented by the shaded regions in Figure 2.3. Note that with improved flight time predictability, this buffer can be reduced at the current level of safety.

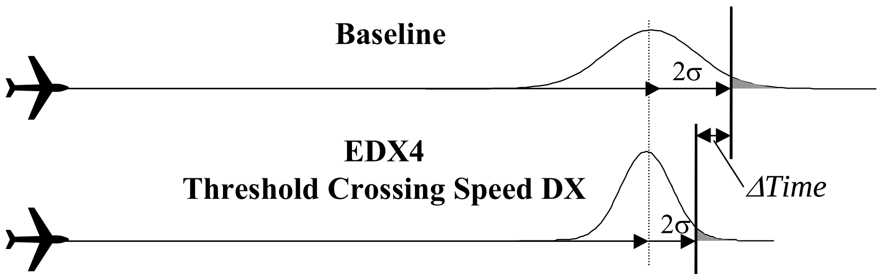


Figure 2.3 Improved EDX4 TRACON Flight Time Prediction

The key EDX4 improvement to CTAS TRACON flight time predictions is in the outer marker to touchdown. Equation (2.3) is used to identify the improvement in flight time predictions under EDX4 exchange of Threshold Crossing Speed (V_{TH}). This equation assumes a 3-stage model, shown in Figure 2.4, to estimate the flight time from the outer marker to the runway threshold, based on previous analysis of aircraft TRACON flight performance [31, 34]. To isolate the EDX4 improvement in TRACON flight time accuracy, Threshold speed(V_3) values of ($\mu \pm 2\sigma$) were inserted in Equation (2.3), while keeping all other parameter assumed mean values consistent with Table 1.1 assumptions.

$$T_{OM-FA} = T_1 + T_2 + T_3 \tag{2.3}$$

where:

$$T_1 = \frac{R_1}{(V_{OM} - V_{TH})} \tag{2.3a}$$

$$T_2 = \frac{(V_{OM} - V_{TH})}{[0.01(V_{OM} - V_{TH}) + 0.6]} \tag{2.3b}$$

$$T_3 = \frac{R - (V_{OM} - V_W)T_1 - \dfrac{(V_{OM} - V_{TH})((V_{OM} + V_{TH} - 2V_W)}{2[0.01(V_{OM} - V_{TH}) + 0.6]}}{(V_{TH} - V_W)} \tag{2.3c}$$

and: T_i = Flight time of segment i
R_i = Range distance of segment i
V_i = Groundspeed at outer marker (OM), runway threshold (TH), or wind (w)
a = Final approach deceleration, approximated by $[0.01(V_1\text{-}V_3) + 0.6]$ (2.3d)

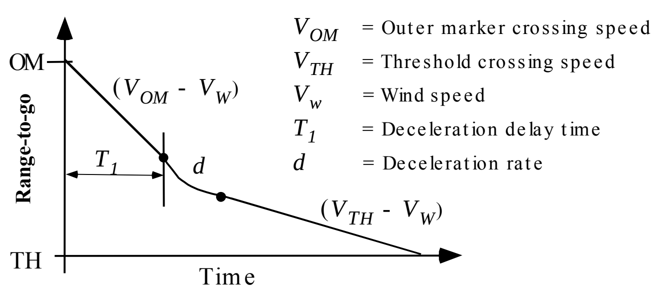


Figure 2.4 Outer Marker to Final Approach Trajectory Model

The resulting 7-second 2σ reduction with EDX4 is assumed to represent the potential reduction in TRACON flight time variation, at a 95 percent confidence level. Thus, the optimal EDX4 TRACON Delay Setting is assumed to be 7 seconds less than the optimal

EDX3 TMA setting, discussed above. This assumption is reflected as the optimal TRACON delay setting in Table 2.4a and Table 2.4b.

Table 2.4a DFW Delay Distribution Fuel Savings Calculation, Passive Baseline

	DFW Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec)						Fuel burn Savings ($)			
			Passive BL	EDX1	EDX2	EDX3	EDX4		EDX1	EDX2	EDX3	EDX4
Rush 1	Straight-In	7	78	77	77	75	68	Per Arr	$0.08	$0.08	$0.23	$0.77
	Downwind	10						Per Arr	$0.08	$0.08	$0.23	$0.77
								Per Rush	$1	$1	$4	$13
Rush 2	Straight-In	18	115	114	114	110	103	Per Arr	$0.08	$0.08	$0.38	$0.92
	Downwind	9						Per Arr	$0.08	$0.08	$0.38	$0.92
								Per Rush	$2	$2	$10	$25
Rush 3	Straight-In	23	131	131	130	126	119	Per Arr	-	$0.08	$0.38	$0.92
	Downwind	12						Per Arr	-	$0.08	$0.38	$0.92
								Per Rush	$0	$3	$13	$32
Rush 4	Straight-In	52	171	170	170	164	157	Per Arr	$0.08	$0.08	$0.54	$1.07
	Downwind	26						Per Arr	$0.08	$0.08	$0.54	$1.07
								Per Rush	$6	$6	$42	$84
Rush 5	Straight-In	28	147	147	146	141	134	Per Arr	-	$0.08	$0.46	$1.00
	Downwind	19						Per Arr	-	$0.08	$0.46	$1.00
								Per Rush	$0	$4	$22	$47
Rush 6	Straight-In	39	170	169	168	163	156	Per Arr	$0.08	$0.15	$0.54	$1.07
	Downwind	36						Per Arr	$0.08	$0.15	$0.54	$1.07
								Per Rush	$6	$11	$40	$80
Rush 7	Straight-In	30	153	153	152	147	140	Per Arr	-	$0.08	$0.46	$1.00
	Downwind	23						Per Arr	-	$0.08	$0.46	$1.00
								Per Rush	$0	$4	$24	$53
Rush 8	Straight-In	64	175	174	173	168	161	Per Arr	$0.08	$0.15	$0.54	$1.07
	Downwind	21						Per Arr	$0.08	$0.15	$0.54	$1.07
								Per Rush	$7	$13	$46	$91
Rush 9	Straight-In	47	185	184	183	177	170	Per Arr	-	-	$0.61	$1.15
	Downwind	60						Per Arr	$0.08	$0.15	$0.61	$1.15
								Per Rush	$5	$9	$66	$123
Rush 10	Straight-In	28	162	161	161	156	149	Per Arr	$0.08	$0.08	$0.46	$1.00
	Downwind	36						Per Arr	$0.08	$0.08	$0.46	$1.00
								Per Rush	$5	$5	$29	$64

Table 2.4b DFW Delay Distribution Fuel Savings Calculation, Active Baseline

			Optimal TRACON Delay Setting (sec)				Fuel burn Savings ($)			
	Approach Procedure	Rush Ops	Active BL	EDX1	EDX2/3	EDX4		EDX1	EDX2/3	EDX4
Rush 1	All	17	16	14	12	5	Per Arr	$0.15	$0.31	$0.84
							Per Rush	$3	$5	$14
Rush 2	All	27	24	21	17	10	Per Arr	$0.23	$0.54	$1.07
							Per Rush	$6	$14	$29
Rush 3	All	35	27	24	20	13	Per Arr	$0.23	$0.54	$1.07
							Per Rush	$8	$19	$38
Rush 4	All	78	36	31	25	18	Per Arr	$0.38	$0.84	$1.38
							Per Rush	$30	$66	$107
Rush 5	All	47	31	27	22	15	Per Arr	$0.31	$0.69	$1.22
							Per Rush	$14	$32	$58
Rush 6	All	75	35	31	25	18	Per Arr	$0.31	$0.77	$1.30
							Per Rush	$23	$57	$98
Rush 7	All	53	32	28	23	16	Per Arr	$0.31	$0.69	$1.22
							Per Rush	$16	$37	$65
Rush 8	All	85	36	32	26	19	Per Arr	$0.31	$0.77	$1.30
							Per Rush	$26	$65	$111
Rush 9	All	107	38	33	27	20	Per Arr	$0.38	$0.84	$1.38
							Per Rush	$41	$90	$147
Rush 10	All	64	34	29	24	17	Per Arr	$0.38	$0.77	$1.30
							Per Rush	$24	$49	$83

Economic Analysis

The fuelburn savings from shifting delay from the TRACON to the Center airspace is determined for each arrival rush and multiplied by the frequency of using each approach category in each rush. The savings are calculated for each rush period, as the TRACON delay setting is dependent upon the rush size (N). Savings are further defined by categories of TRACON approach geometry. The DFW calculations are included in Table 2.4a and 2.4b for DFW, with ATL and LAX values in Appendix D. Note that only some TRACON routes and their corresponding rush arrival aircraft are able to absorb the optimal TRACON Delay Setting within the Passive Baseline case, and thus do not incur the associated fuel savings from EDX. Table 2.5 summarizes the daily savings of all airports.

Table 2.5 Center/TRACON Delay Distribution Daily Fuel Savings Summary

	Passive Baseline				Active Baseline		
	EDX1	EDX2	EDX3	EDX4	EDX1	EDX2/3	EDX4
ATL							
ARTCC Delay Shift (sec)	0-1	0-2	6-8	13-15	4-5	8-11	15-18
Fuel Savings ($/op)	0-0.09	0-0.18	0.54-0.73	1.18-1.36	0.36-0.45	0.73-1.00	1.36-1.63
($/rush)	2-5	2-10	22-79	47-148	15-53	29-116	54-190
($/day)	$33	$56	$204	$910	$290	$661	$1112
DFW							
ARTCC Delay Shift (sec)	0-1	0-2	3-8	10-15	2-5	4-11	11-18
Fuel Savings ($/op)	0-0.08	0-0.15	0.23-0.61	0.77-1.15	0.15-0.38	0.31-0.84	0.84-1.38
($/rush)	0-7	1-11	4-66	13-123	3-41	5-90	14-147
($/day)	$31	$58	$296	$611	$192	$435	$750
LAX							
ARTCC Delay Shift (sec)	0-2	0-3	5-9	12-16	4-6	8-13	15-20
Fuel Savings ($/op)	0-0.16	0-0.24	0.40-0.71	0.95-1.27	0.32-.048	0.63-1.03	1.19-1.59
($/rush)	0-18	2-27	12-154	29-274	10-103	20-223	37-342
($/day)	$30	$50	$334	$629	$225	$478	$773

The daily DFW savings are extrapolated to an annual level and to other NAS airports by accounting for the total number of 1996 operations at each facility. NAS benefits are calculated based on EDX deployment in the Center airspace surrounding 37 candidate airport sites. This set was chosen to represent high-demand NAS airports, include FAA FFP1 and phase 2 deployment locations. The simple extrapolation used here employs Equation (2.4) to estimate benefits, as employed in other studies [13].

$$\textit{Annual Savings} = (\textit{Annual Ops}) \times (\textit{Rush Arrivals}_{DFW}) \times (\textit{Apt Factor}) \times (\textit{Savings Per Interrupt}) \quad (2.4)$$

where: *Annual Ops* = Annual airport operations (00s) (Appendix C)
Rush Arrivals$_{DFW}$ = DFW number of rush arrivals per 100 daily airport operations (Appendix C)
Apt Factor = Factor accounting for local airport rush arrival frequency relative to DFW, based on FAA delay data (Appendix C)
Savings Per Interrupt = Average cost savings per rush arrival (Table 2.6)

As in the other evaluations, DFW rush arrival rates were adjusted by an *Airport Factor* to account for variations in congestion at each facility. Airports with less overall delays are assumed to require disproportionately fewer metering conformance actions. Thus, airports with less demand-capacity congestion are assumed to delay fewer en route arrival and departure aircraft to meet airport-scheduling constraints. An individual airport's assumed delayed arrival rates is adjusted from the nominal DFW value of Table 2.6, using FAA delay data [35]. These data record delays at each airport in excess of 15 minutes in CY1996, including both arrivals and departures. This metric hides the significant number of smaller delays during an arrival rush period and includes delayed departures, making it a gross indicator of the airport's level of delayed arrival flights. Despite these limitations, this data provided a reasonable factor for extrapolating the detailed traffic analyses (at 3 airports) to the 37-NAS airports. To do so, the NAS airports were broken into five delay categories. Engineering judgement was used to assign each category a rush arrival rate relative to DFW. Simulated rates [13] of 130%, 115%, 100%, 80%, and 60% for airport delay classes 1, 2, 3, 4, and 5 were used, as shown in Table 2.6. The FAA delay data and criteria used to assign delay classes are included in Appendix C.

The three-airport average rush arrival rates and cost savings observed in the daily simulation are summarized in Table 2.6 and used in Equation (2.4). Note that the average rush arrival rate was increased slightly to match metered arrival frequencies identified in previous studies in order to be consistent with the other benefits assessments in this report.

Table 2.6 EDX Average Delayed Arrivals Frequency and Savings

	EDA Daily Center/TRACON Delay Distribution Benefits							
	Passive Baseline				Active Baseline			
	ATL	DFW	LAX	Average	ATL	DFW	LAX	Average
Rush Operations Rate (per 100 Airport Ops)	35.7	27.0	27.0	30.4*	35.7	27.0	27.0	30.4*
Average Fuel Savings ($/op)	$0.05	$0.05	$0.06	$0.05	$0.41	$0.33	$0.42	$0.39
EDX1	$0.08	$0.10	$0.09	$0.09	$0.93	$0.74	$0.90	$0.86
EDX2	$0.65	$0.50	$0.63	$0.60	--	--	--	--
EDX3	$1.28	$1.04	$1.18	$1.18	$1.57	$1.27	$1.45	$1.44
EDX4								

* Assumes average delayed arrival rates from reference [13] to maintain consistency between EDA benefit estimates.

The annual airport operations [36] and resulting annual savings by airport using Equation (2.4) are shown in Table 2.7. The annual savings are plotted graphically by airport in Figure 2.5. The large hub airports, ORD, DFW, ATL, and LAX, achieved significant gain from EDX, saving over $270,000 and $330,000 per year relative to a Passive and Active Baseline, respectively. Passive Baseline savings are lower because many cases were restricted by the maximum TRACON delay that could be absorbed along each route. Under the Passive Baseline, the largest en route benefit came from the EDX4, Runway Threshold Speed and EDX3, Speed Intent. Because EDA accounted for the speed intent improvements under the Active Baseline, EDX3 saw no savings, with the bulk again attributed to EDX4. Benefits at all 37-airports, representing NAS-wide deployment, totaled $4.9M and $6.0M annually, relative to the Active and Passive Baselines respectively. As noted earlier, additional and possibly more significant benefits would be expected with the integration of data exchange with TRACON automation tools, such as Active FAST using EDX4 [34]. The benefits shown here are limited to those achieved through Center-deployed DSTs.

Results Summary

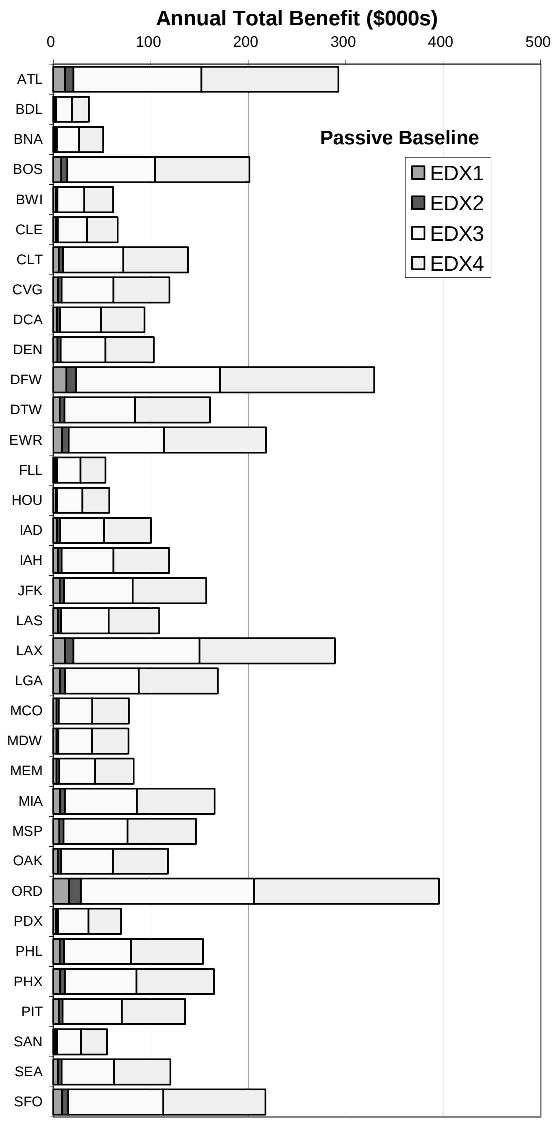
This chapter evaluated EDX Center/TRACON delay distribution benefits. Reduced variance in EDX arrival metering fix delivery accuracy and EDX4 TRACON time-to-fly predictions, results in arrival flight efficiency benefits due to the ability to absorb delay more efficiently in Center airspace while still maintaining a given TRACON entry rate. More savings were found with the Active Baseline case, as this case was less restricted by the maximum controllability window of the various approach routes. Relative to the Passive Baseline, it was found that EDX shifted 11-20 seconds of rush arrival delay from TRACON to Center airspace. This saved an average of 12 lbs of fuel or $1.18 per rush arrival ($93 per average rush), with a total savings of $4.9M annually assuming NAS-wide deployment at 37-airports. Relative to an Active Baseline, it was found that EDX shifted 11-20 seconds of rush arrival delay from TRACON to Center airspace. This saved 14 lbs of fuel or $1.44 per rush arrival ($118 per average rush), with a total savings of $6.0M annually NAS-wide.

The EDX benefits were evaluated relative to a FFP1 Baseline, which includes TMA. A rough indication of the Center/TRACON delay distribution benefits of EDX relative to other ATM DSTs can be made by using Figure 2.2 and the arrival metering fix delivery accuracy values (1-sigma) of 180 seconds [22] prior to TMA, 90 seconds with TMA, and 15-20 seconds with EDA [20]. Note that through TMA implementation, the maximum delay absorption capability of a route (typically 100-300 seconds) would likely require a TRACON delay setting below optimal. Thus, despite TMA's significant improvement in metering fix delivery accuracy, little change would occur in the TRACON delay setting, allowing only limited shifting of delay to more fuel-efficient ARTCC airspace. Post-TMA, improvements to the metering fix accuracy, such as with EDX, enables a reduction in TRACON delay along the optimal line, resulting in significantly higher benefits per metering fix accuracy improvement.

To achieve these benefits, it is assumed that TRACON traffic management coordinators would be comfortable in shifting delay upstream (i.e., less TRACON front-loading) with the more accurate metering fix delivery schedule adherence of these DSTs. Additionally, the study would benefit from a better understanding of the controllability window (minimum/maximum TRACON delay setting) of various TRACON arrival routes at various ATM facilities. Another key assumption driving these estimates is that aircraft fuelburn rates for absorbing delay are 1.5 times larger in TRACON relative to ARTCC airspace. This assumption should be calibrated with field data, and may differ under Passive and Active Baseline (including EDA) metering conformance delay strategies. Alternatively, higher fidelity aircraft trajectory and fleet mix models could be employed to improve fuel burn estimates.

Table 2.7 EDX Center/TRACON Delay Distribution Benefits

Airport	Annual Airport Ops (000s)	Apt Delay Delays/Category		Rush Arrival Rate*	Annual Cost Saving ($000s, 1998)						
					Passive Baseline				Active Baseline		
					EDX1	EDX2	EDX3	EDX4	EDX1	EDX2/3	EDX4
Atlanta (ATL)	773	23.88	3	30.4	12.1	21.0	139.8	275.8	90.7	201.8	337.8
Nashville (BNA)	226	1.36	5	18.2	1.5	2.6	17.5	34.4	11.3	25.2	42.2
Boston (BOS)	463	0.73	2	18.2	2.1	3.7	24.6	48.5	15.9	35.5	59.4
Bradley (BDL)	161	26.37	5	34.9	8.3	14.4	96.2	189.9	62.4	138.9	232.5
Baltimore (BWI)	270	3.67	5	18.2	2.5	4.4	29.3	57.9	19.0	42.3	70.9
Cleveland (CLE)	291	4.68	5	18.2	2.7	4.7	31.6	62.3	20.5	45.6	76.3
Charlotte (CLT)	457	6.55	4	24.3	5.7	9.9	66.2	130.5	42.9	95.5	159.9
Cincinnati (CVG)	394	10.38	4	24.3	4.9	8.5	57.0	112.4	36.9	82.2	137.6
Washington National (DCA)	310	6.53	4	24.3	3.9	6.7	44.8	88.5	29.1	64.7	108.3
Denver (DEN)	454	1.90	5	18.2	4.3	7.4	49.3	97.3	32.0	71.2	119.2
Dallas – Ft. Worth (DFW)	870	19.59	3	30.4	13.6	23.6	157.4	310.5	102.1	227.2	380.3
Detroit (DTW)	531	9.10	4	24.3	6.6	11.5	76.9	151.7	49.9	111.0	185.8
Newark (EWR)	443	65.25	1	39.5	9.0	15.6	104.3	205.8	67.6	150.6	252.0
Ft. Lauderdale (FLL)	236	1.53	5	18.2	2.2	3.8	25.7	50.6	16.6	37.0	62.0
Houston Hobby (HOU)	252	2.57	5	18.2	2.4	4.1	27.4	54.0	17.8	39.5	66.2
Washington Dulles (IAD)	330	6.81	4	24.3	4.1	7.2	47.8	94.4	31.0	69.0	115.6
Houston–Intercontinental (IAH)	392	11.45	4	24.3	4.9	8.5	56.7	111.9	36.8	81.9	137.1
N.Y. Kennedy (JFK)	361	29.53	2	34.9	6.5	11.3	75.0	148.0	48.7	108.3	181.3
Las Vegas (LAS)	480	3.68	5	18.2	4.5	7.8	52.1	102.7	33.8	75.2	125.8
Los Angeles (LAX)	764	24.13	3	30.4	11.9	20.7	138.2	272.7	89.7	199.5	334.0
N.Y. LaGuardia (LGA)	343	46.22	1	39.5	7.0	12.1	80.6	159.0	52.3	116.3	194.7
Orlando (MCO)	342	4.59	5	18.2	3.2	5.6	37.1	73.2	24.1	53.6	89.7
Chicago Midway (MDW)	254	6.70	4	24.3	3.2	5.5	36.8	72.6	23.9	53.1	89.0
Memphis (MEM)	364	NA	5	18.2	3.4	5.9	39.5	77.9	25.6	57.0	95.5
Miami (MIA)	546	6.79	4	24.3	6.8	11.9	79.1	156.1	51.3	114.2	191.1
Minneapolis (MSP)	484	9.29	4	24.3	6.0	10.5	70.0	138.1	45.4	101.0	169.1
Oakland (OAK)	516	NA	5	18.2	4.8	8.4	56.1	110.6	36.4	80.9	135.5
Chicago O'Hare (ORD)	909	34.46	2	34.9	16.3	28.4	189.2	373.2	122.7	273.1	457.1
Portland (PDX)	306	2.41	5	18.2	2.9	5.0	33.2	65.5	21.5	47.9	80.3
Philadelphia (PHL)	406	17.95	3	30.4	6.3	11.0	73.5	145.0	47.7	106.1	177.6
Phoenix (PHX)	544	7.25	4	24.3	6.8	11.8	78.8	155.4	51.1	113.7	190.4
Pittsburgh (PIT)	447	6.60	4	24.3	5.6	9.7	64.8	127.8	42.0	93.5	156.5
San Diego (SAN)	244	3.31	5	18.2	2.3	4.0	26.4	52.2	17.2	38.2	63.9
Seattle (SEA)	398	6.37	4	24.3	5.0	8.6	57.5	113.5	37.3	83.1	139.1
San Francisco (SFO)	442	56.57	1	39.5	9.0	15.6	104.0	205.2	67.5	150.2	251.4
Salt Lake City (SLC)	374	3.53	5	18.2	3.5	6.1	40.6	80.1	26.3	58.6	98.1
St. Louis (STL)	517	34.04	2	34.9	9.3	16.2	107.6	212.4	69.8	155.4	260.1
37-Airport Total/Average	430	---		---	215	374	2,493	4,917	1,617	3,598	6,023



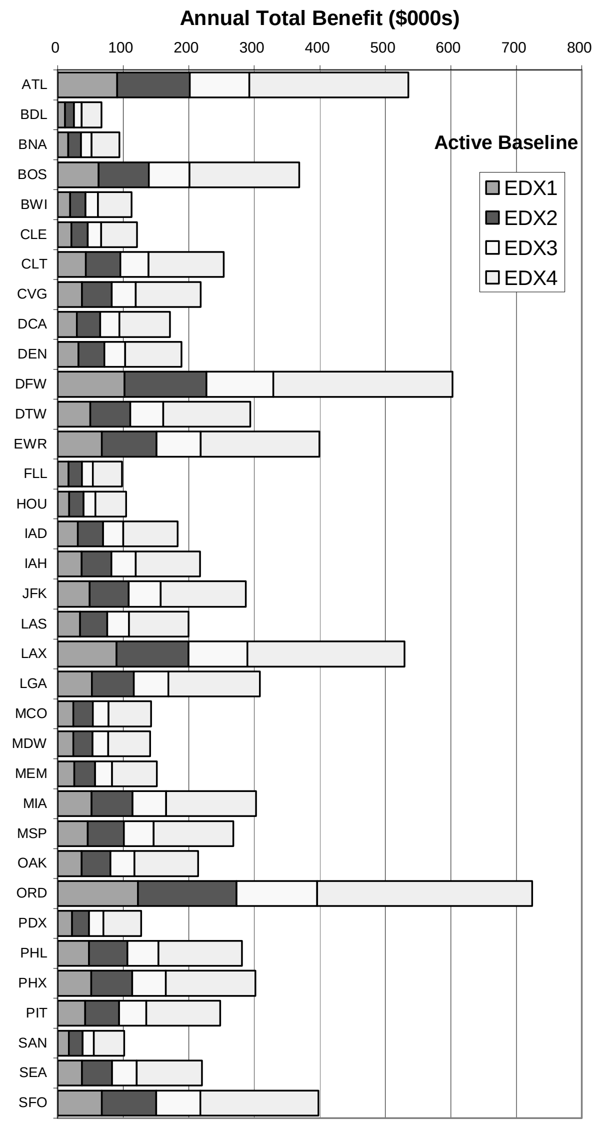


Figure 2.5 EDX Center/TRACON Delay Distribution Benefits

3 FMS Descent Speed Profile Benefits

Current DST operations assume nominal descent/climb speed and altitude profiles based on nominal aircraft type-specific performance, defined in static DST databases. Airlines operate a specific fleet with unique characteristics and may have specific policies on climb/descent procedures in line with their operating objectives (e.g., shorter scheduled flight times than their competitors). Thus, data exchange can augment the static DST database with specific speed profiles by airline and/or aircraft tail number. Additionally, since conditions at the time of descent are frequently quite different than those anticipated during pre-flight planning, real-time downlink of FMS descent speed preferences could be beneficial. If the particular aircraft is not delayed due to airport capacity restrictions, the preference can be accommodated directly, improving user flexibility and ATM trajectory prediction accuracy. During delayed operations, DSTs can uplink an arrival fix required time of arrival (RTA), which the FMS can use to calculate optimal top-of-descent (TOD) and descent speed profile and downlink for use in ATM DSTs. This FMS computed speed profile is assumed to be more fuel-efficient than DST calculations alone. The data exchange negotiation of this FMS speed profile is evaluated in this chapter.

During typical arrival operations, the CTAS Traffic Management Advisor (TMA) will schedule meter-fix times of arrival (STAs) to optimize the arrival flow into the terminal area. During airport rushes when controllers meter arrival traffic, EDA generates descent advisories (speed profile, altitude, and vector maneuvers) to conform to a required time of arrival (RTA) at the TRACON arrival fix, while minimizing fuel and deviations from the user's preferred trajectory. As reference [37] shows, EDA-calculated advisories significantly increase the use of speed control as a delay strategy compared with controller-developed delay strategies. The EDA speed advisories, one of several delay methods, are based on simple heuristics developed over several years of controller performance observation and may differ from the speed profiles computed on board aircraft equipped with a RTA-capable Flight Management System (FMS). EDA must compute speed advisories for all aircraft types that are acceptable by controllers, whereas FMS RTA functions may be designed to determine optimum speed profiles based on proprietary performance data and policy for a specific aircraft type and specific user. Thus ATM DST-FMS data exchange has the potential of generating more fuel-efficient arrival trajectories than the DST alone.

Several options exist to improve the fuel efficiency of DST speed strategies. In all cases, improvement requires that the DSTs be provided with additional data. At one extreme, the airframe and FMS manufacturers could provide DSTs with the optimal-speed data (used for FMS) to support real-time DST computations. Secondly, the DST performance model database could be analyzed to develop a surrogate set of optimal data for each type. Alternatively, DST speeds could be improved through real-time data exchange with the aircraft users. Properly equipped aircraft could "negotiate" with ATM DSTs by data-linking their desired RTA-based TOD and speed profiles directly to ATM in real time. Assuming that such an exchange was operationally feasible, this chapter identifies the benefits of this negotiation, assuming the required FMS equipage.

Analysis Process

The benefits methodology process employed in previous research [14] is described below. The sequence of analytical formulations and computer-based modelings follows the Figure 1 approach (and numbering) of the introduction summary section. Initially technology definitions for baseline and EDX case are defined (1). ATM descent speed strategies (2) with and without data exchange are specified. When these strategies and their associated per operation fuel savings are combined with a daily traffic scenario (3), which identifies the applicable metered arrival aircraft, daily fuel savings are estimated. The resulting DFW daily fuel savings are then extrapolated to annual and NAS-wide levels (4). These model components are discussed in more depth with the analysis results in the following sections.

Study Cases

The analysis process is initiated by identifying the various candidate technologies, and their capabilities, that may be associated with FMS Descent Speed Profile benefits. The EDX cases evaluated under this benefit mechanism include EDX6 relative to an Active Baseline. Cases evaluated included:

- **Active Baseline + EDX1-2** – TMA/EDA with Weather and Aircraft Weight data exchange
- **EDX6 – Weather, Weight, RTA/Speed Preference** Data Exchange

In both cases, it is assumed that the FMS and CTAS speed strategies makes use of common meteorological (wind, temperature) forecasts and aircraft weight data, via data exchange (e.g., EDX1 and EDX2 scenarios). In this analysis focus is on the speed control delay strategy. Arrival metering delays unable to be absorbed by speed control are ignored.

Under EDX6, the EDA speed advisory is assumed to be replaced with the FMS user-preferred speed profile, involving a simple real-time "negotiation" between CTAS and the aircraft FMS. Initially an arrival-fix metering fix required time of arrival (RTA) restriction, assumed to be calculated by TMA, is uplinked to the aircraft. The flight crew then uses the on-board FMS RTA capability to generate an optimum speed profile to meet the metering fix time restriction. This FMS-computed TOD and Mach/CAS descent speed profile is downlinked as an user preferred trajectory. Full equipage of FMS trajectory optimization and RTA guidance capabilities is assumed.

Arrival Metering Delay

Initially an en route set of air-traffic "demand" trajectories for a typical day within a block of en route airspace was defined. In this study the Fort Worth Air Route Traffic Control Center (ZFW) airspace was analyzed, including arrival, departure, and overflight traffic operations between 40 and 250 nautical miles (nm), at or above 10,000 ft from Dallas-Fort Worth International Airport (DFW). Enhanced Traffic Management System (ETMS)-based flight trajectories for a typical day (Friday, June 14, 1996) were used to generate "undelayed" trajectories, trajectories for approximately 2,500 DFW arrivals and departures [33], representing what each flight would do if left alone to fly the user's preferred trajectory. EDA was also assumed to enable direct routing to the arrival-metering fix. These trajectories, shown in Figure 3.1 define the arrival congestion traffic scenario.

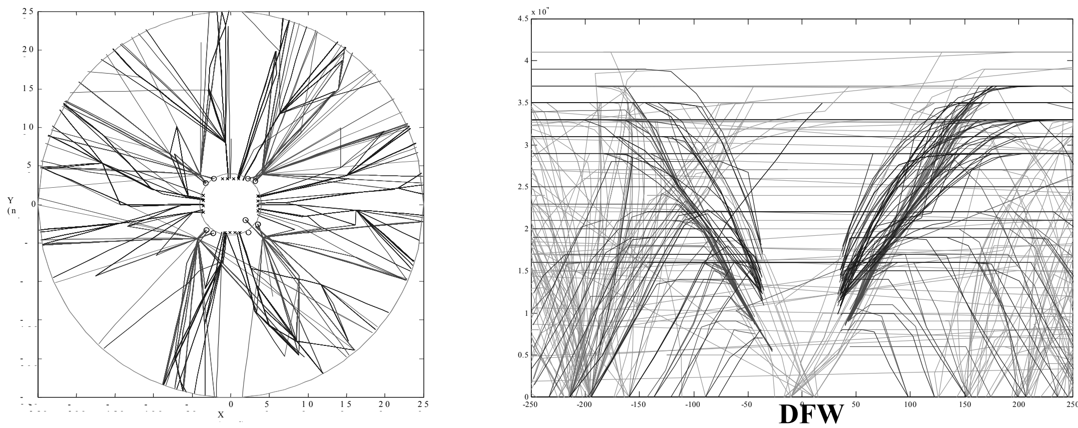


Figure 3.1 Plan and Profile View of DFW Study Day Operations

During peak periods, controllers meter DFW arrival flights to meet airport capacity restrictions. A simplified model of TMA metering was developed to estimate metering delays for each DFW arrival. Meter-fix scheduled times of arrival (STAs) at the TRACON boundary, and associated delays, were based on maximum TRACON entry rates and minimum inter-arrival fix separations, as shown in Table 3.1.

Table 3.1 DFW Scheduling Criteria

Scheduling Criteria	Assumed Value
Minimum Arrival Meter-Fix Separation	5.50 nm
Maximum TRACON Arrival Rate (4 Arrival	150 ac/hr

Speed control, under evaluation in this chapter, can only absorb 1-2 minutes of delay. Thus, delays in excess of the maximum speed control delay were ignored for this benefit mechanism. Figure 3.2 shows a distribution of the arrival delays required to meet the Table 3.1 constraints over the course of the sample day. Only those of 2 min. delay or less were examined.

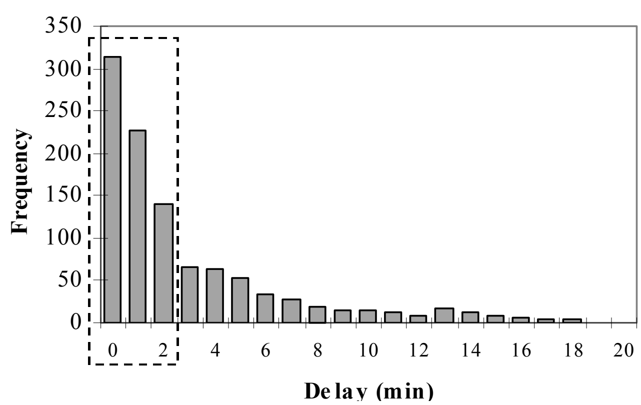


Figure 3.2 TMA Arrival Delays

CTAS and FMS Speed Strategy

The particular speed strategies used to absorb the arrival metering delay differ between FMS and ATM strategies. Both are assumed to employ the standard Mach/CAS descent altitude-speed profile in a typical descent from the cruise altitude (35,000 ft) to the metering fix altitude (10,000 ft) over a range of 150 nm, to meet a MF RTA.

Mach/CAS descents employ a descent speed profile characterized by a constant Mach segment followed by a constant calibrated airspeed (CAS) segment, performed at idle thrust for maximum fuel efficiency. This also included placement of the TOD. The assumed descent trajectory is divided into five stages, as shown in Figure 3.3.

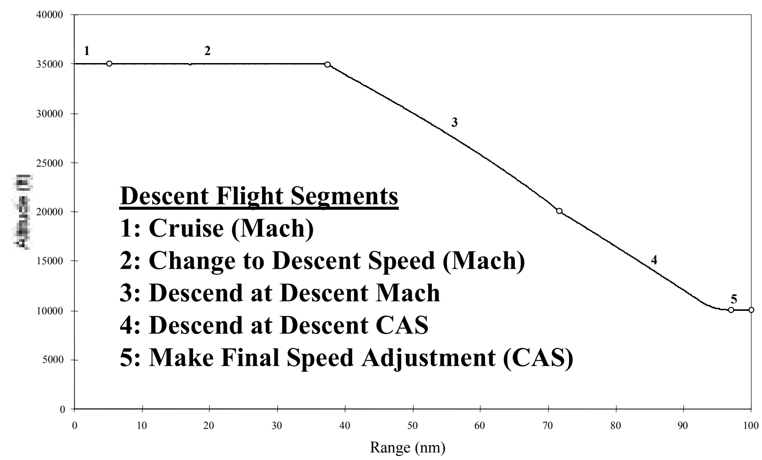


Figure 3.3 Simulated Five-Segment Descent Profile

Each strategy aims to predict an efficient descent-speed profile to meet a metering fix crossing time, assumed to require delay absorption from the nominal descent trajectory. Both cruise speed and descent speed along with TOD can be adjusted to meet the required time of arrival (RTA), at a constant range to fly.

<u>CTAS Descents</u>

When determining the speed profile required for a given RTA, the EDA first evaluates the time of arrival of the aircraft at the metering fix using a default descent profile. The default descent profile is specified by the airspeed of the constant CAS descent segment (Segment 4), and can be changed within the CTAS logic. The default cruise speed is the current (Segment 1) cruise speed. If the time of arrival calculated using the default profile requires delay, EDA shortens the descent duration using on one of three speed strategies.

Under the C=D strategy assumed in this analysis, if the aircraft must reduce its speed to meet a metering fix crossing time, the descent speed is set to essentially “balance” cruise and descent CAS speeds. The higher of cruise/descent CAS is initially decremented until both speeds are equal. Then each speed is alternately decremented. This strategy attempts to reduce the need for significant speed changes between cruise and descent by bringing the cruise and descent speeds closer. Although actual controller techniques may not be so precise, this approach conservatively approximates controller actions.

FMS (Fuel-Optimal) Descents

Given a metering fix RTA uplinked from CTAS, the FMS computes a fuel-optimal Mach/CAS descent profile. FMS descents are optimistically represented in this study as the fuel-optimal descent speed profile. This assumes that the RTA-capable FMS would be able to calculate the minimum fuel descent to meet the metering fix RTA. An actual FMS is likely to achieve similar, but less fuel-efficient results. Additionally, the fuel-optimal Mach/CAS speed pairs may not reflect operational practices such as multiple speed changes during a single approach trajectory.

Speed Strategy Fuelburn

The descent fuelburn characteristics were evaluated in a high-fidelity simulation [50] for two aircraft types (MD80 and B747) under both FMS and CTAS speed control strategies. In each case, accurate aerodynamic and propulsion performance models were used to simulate aircraft trajectories and fuelburn estimates. Simulations were performed using over a range of Mach/CAS descent speed combinations for each aircraft. From the simulations, contours of fixed-time and fixed-fuel consumption as functions of approach speed were generated over a fixed-range to the arrival-metering fix. The contours were then used to determine the fuel consumed under both the FMS and CTAS strategies. The two aircraft high-fidelity simulation results were extrapolated fleet-wise with scaling factors based on Eurocontrol Base of Aircraft Data (BADA) [38] aircraft performance characteristics. More details on the high fidelity simulations can be found in reference [14].

Figure 3.4 maps all combinations of Mach (y-axis)/CAS (x-axis) descent pairs over reasonable speed range of two aircraft types. On each plot two sets of contours identify the fuelburn and time of each Mach/CAS speed profile, as solid and dashed lines, respectively. Locations of minimum fuel for each descent duration are marked with an asterix. This curve is assumed to represent the hypothetical FMS performance. Square boxes are used to represent the CTAS speed combinations, assumed to be issued to the aircraft without data exchange.

When the fuelburn information of Figure 3.4 is plotted against descent duration or metering fix required time of arrival (RTA), as in Figure 3.5, CTAS-FMS negotiation fuel savings can be estimated. Using these Fuel/RTA plots, the effect of different speed control strategies on fuelburn can be determined for a particular aircraft RTA.

Figure 3.6 transforms the plot from RTA-based (Fig. 3.5) to delay-based values, assuming a nominal Mach/CAS speeds. The indicated “nominal descent” cases are based on airline operations manuals [39-40]. This represents the zero delay point, with larger RTAs representing the speed control delayed operations. The portions of the Figure 3.5 plots, with delay (relative to the nominal RTA) as the x-axis are shown in Figure 3.6.

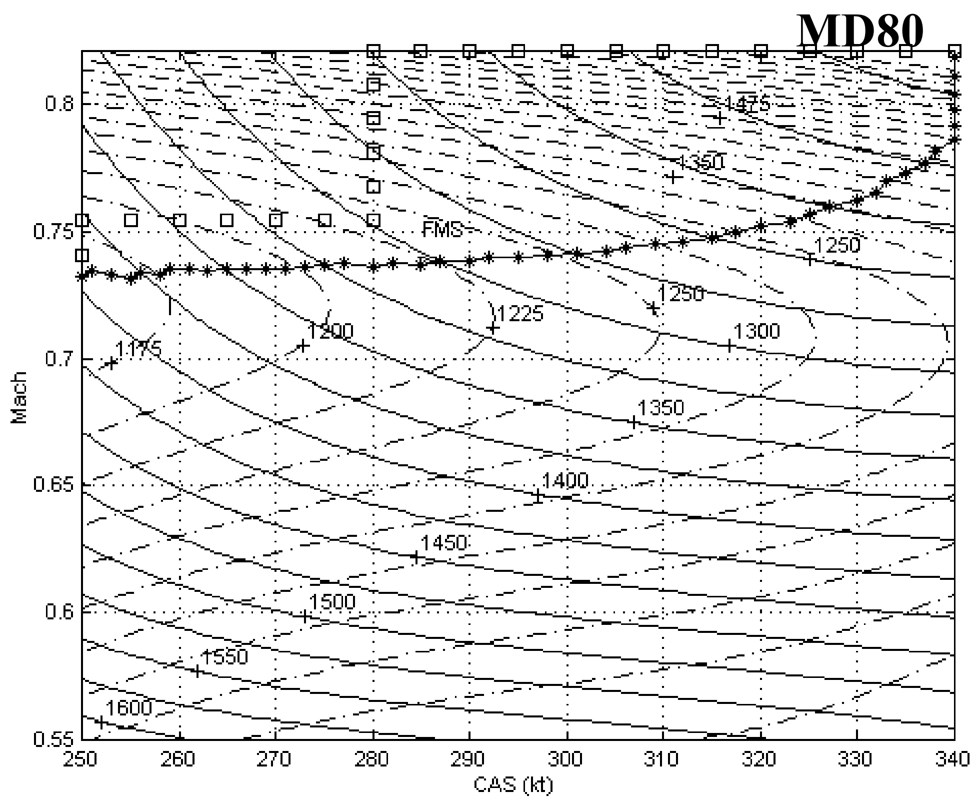


Figure 3.4a Mach/CAS Plots for the MD80 Aircraft

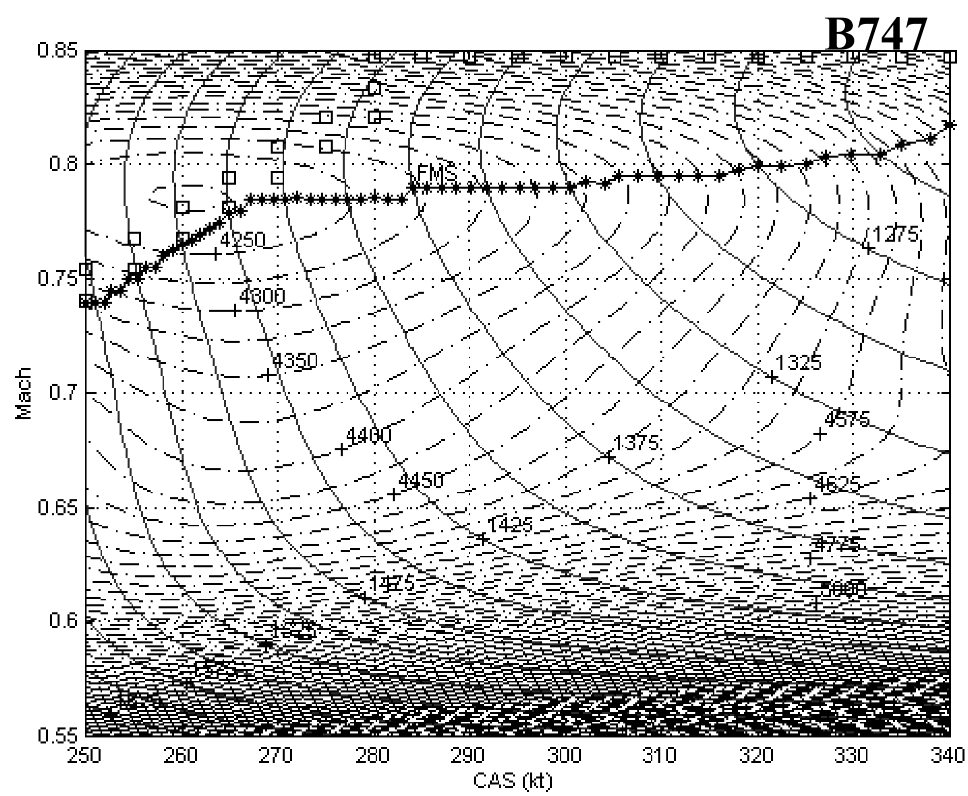


Figure 3.4b Mach/CAS Plots for the B747 Aircraft

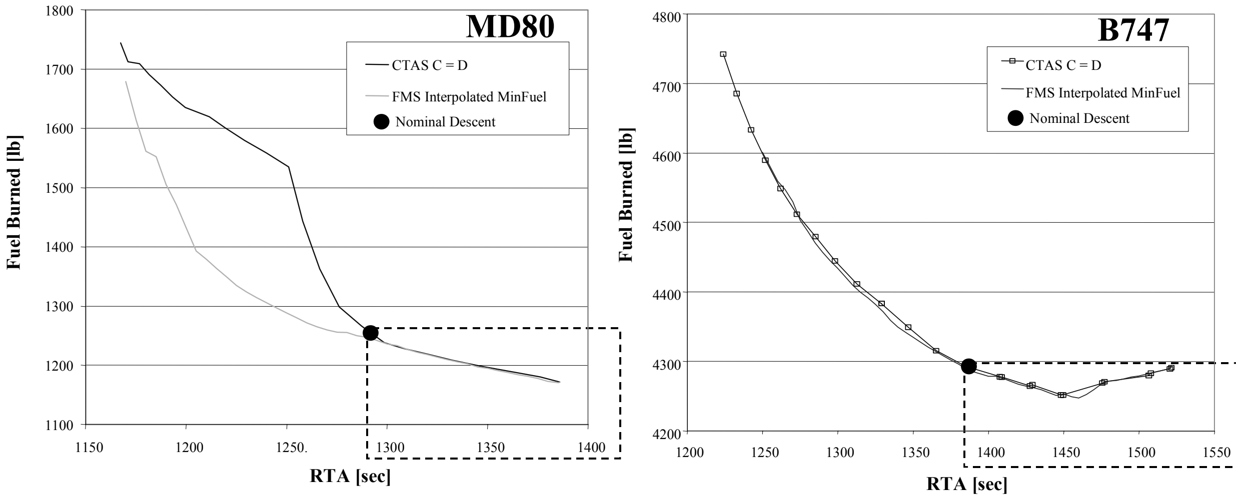


Figure 3.5 Fuel/RTA Plot for the MD80 and B747 Aircraft

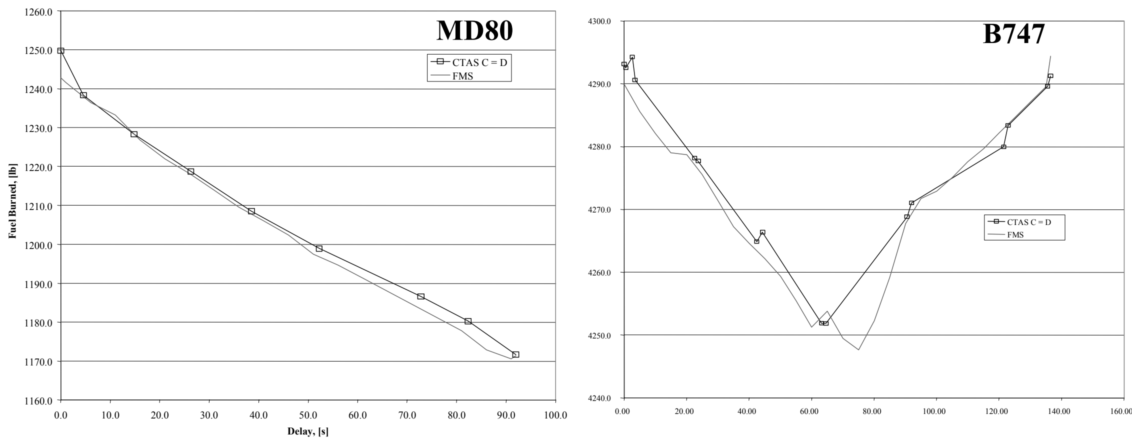


Figure 3.6 Fuel/Delay Plots for the MD80 and B747 Aircraft

A fuel scale factor (FSF) was applied to the high-fidelity MD80 and B747 fuelburn results to reflect variances in aircraft performance across the fleet, based on Eurocontrol's Base of Aircraft Data (BADA) aircraft models [38]. Heavy aircraft were scaled relative to the B747 aircraft; all others were scaled relative to the MD80 aircraft. The FSFs and associated assumptions are included in Appendix E.

Economic Analysis

The daily potential fuel burn savings through the implementation of data exchange on the simulated TMA metered flights are presented in Table 3.2. It is estimated that TMA delayed 70 percent of the simulated 1,047 arrival flights on average 4 minutes with a total of 44.5 minutes of delay. If speed control with full data exchange was used to absorb as much of this delay as possible, a potential fuel savings of almost 2,000 lb could be realized. This averages to nearly 3 lb of fuel per delayed arrival operation, although the median is less than 1 lb, as shown in Figure 3.7. The daily fuel cost savings of Table 3.2 apply a conservative fuel cost of $0.10 per lb.

Table 3.2 DFW FMS Speed Profile Fuel Savings

	Daily Delayed Arrivals	Average Savings Per Rush Arrival Op
Daily Number of DFW Arrival Operations	732 (1)	NA
Daily TMA Delay	44.51 min	3.6 min/op
Daily Fuel Savings	1,991 lb	2.7 lbs/op
Daily Cost Savings (2)	$199	$0.27/op

(1) 70% of all modeled DFW arrivals were delayed.
(2) Assumes fuel cost of $0.10 per lb.

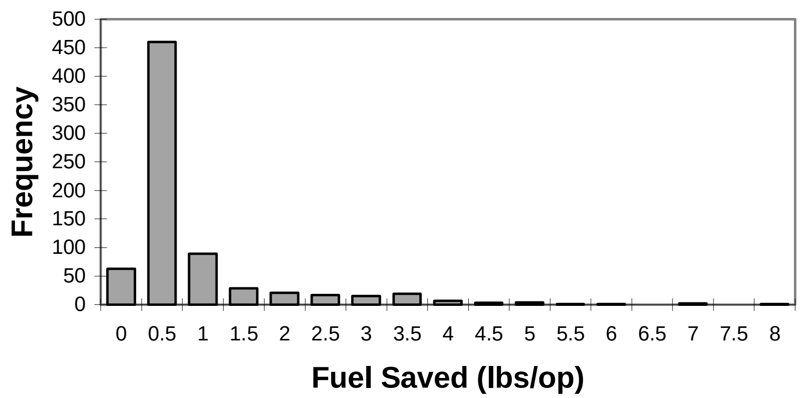


Figure 3.7 Fuel Savings per Operation

As with other benefit mechanisms in this report, these daily DFW savings were extrapolated to an annual NAS-wide level by accounting for the total number of 1996 operations at each facility. As in other chapters, the simple extrapolation employs Equation (3.1) to estimate benefits.

$$\textit{Annual Savings} = (\textit{Annual Ops}) \times (\textit{Rush Arrivals}_{DFW}) \times (\textit{Apt Factor}) \times (\textit{Savings Per Interrupt}) \quad (3.1)$$

where: *Annual Ops* = Annual airport operations (00s) (Appendix C)
Rush Arrivals$_{DFW}$ = DFW number of rush arrivals per 100 daily airport operations (Appendix C)
Apt Factor = Factor accounting for local airport rush arrival frequency relative to DFW, based on FAA delay data (Appendix C)
Savings Per Interrupt = Average cost savings per rush arrival (Table 3.3)

The daily rush arrival rates and costs observed in the daily simulation and used in Equation (3.1) are summarized in Table 3.3.

Table 3.3 DFW Rush Arrival Rates and Costs

Parameter	EDX6
Rush Arrival Rate (per 100 Airport ops)	30.4
Average Savings Per Interrupt Delay	$0.27/op

As in the other evaluations, DFW rush arrival rates were adjusted by an *Airport Factor* to account for variations in congestion at each facility. Airports with less overall delays are assumed to require disproportionately fewer metering conformance actions. Thus, airports with less demand-capacity congestion are assumed to delay fewer en route arrival and departure aircraft to meet airport-scheduling constraints. An individual airport's assumed delayed arrival rates is adjusted from the nominal DFW value of Table 5.5, using FAA delay data [35]. These data record delays at each airport in excess of 15 minutes in CY1996, including both arrivals and departures. This metric hides the significant number of smaller delays during an arrival rush period and includes delayed departures, making it a gross indicator of the airport's level of delayed arrival flights. Despite these limitations, this data provided a reasonable factor for extrapolating the detailed DFW traffic analyses to the 37-NAS airports. To do so, the NAS airports were broken into five delay categories. Engineering judgement was used to assign each category a rush arrival rate relative to DFW. Simulated rates [13] of 130%, 115%, 100%, 80%, and 60% for airport delay classes 1, 2, 3, 4, and 5 were used, as shown in Table 5.6. The FAA delay data and criteria used to assign delay classes are included in Appendix C.

The annual airport operations [36] and annual savings by airport are also shown in Table 3.4. The annual savings are plotted graphically by airport in Figure 3.8. The large hub airports, ORD, DFW, ATL, and LAX, showed savings of over $60,000 per year. Benefits at all 37 airports, representing NAS-wide deployment, totaled almost $0.5M annually. These results assume that EDA can compute speed changes to increment the metering fix RTA by 5 or 10 sec, and that the associated speed changes incorporating FMS speed preferences, are provided by the controller in an accurate and timely way. It should be noted that this analysis assumes underlying calibration of EDA trajectory prediction with the exchange of aircraft wind/temperature (EDX1) and weight (EDX2). It is unknown how much additional benefit results from these data exchanges. Additionally, this analysis could be used to improve the assumed CTAS EDA speed strategies.

An examination was made of the effect of moving the assumed nominal descent speed profile of the MD80 to a different Mach/CAS pair. The values of 0.8M/280kt CAS (replacing 0.76M/280kts) were used as an alternate. Since fuel consumption of most aircraft types were scaled relative to the MD80, a shift in the speed profile and associated fuelburn has an impact. The fuelburn versus RTA plot of Figure 3.5 compares the differences in fuelburn for the optimal FMS and CTAS curves from Figure 3.4. The dotted rectangle represents the region where the aircraft would be slowed down from the nominal operating point to absorb delay. With the nominal point set at 0.76M/280kt, the FMS and CTAS curves are very similar showing negligible fuel savings between the two.

Looking at Figure 3.5 using the modified 0.8M/280CAS nominal speed profile, puts the nominal operating point at an RTA of 1,265 seconds on the upper curve and re-positions the dotted box further up and to the left. At this new operating point small delays of 30 seconds or less (RTAs of 1,295 seconds or less), which represent 15 percent of all delays, save up to 130 lbs per flight when using the downlinked FMS profile. For delays larger than 30 seconds, the savings are again negligible (i.e., FMS and CTAS lines converge). Under this basis, a rough estimate of the savings was found to be $550 per day, an increase of about $350.

However, since most of the modified nominal point benefits occur below 30 seconds, the feasibility of realizing these benefits is questionable. Indeed, it is unclear whether controllers could be sensitized or would negotiate with the aircraft via datalink, for delays less than 15 seconds. Furthermore, the nature of the fuelburn differences between the CTAS and optimal FMS curves of Figure 3.5 is peculiar to the nominal CTAS speed profile used to mechanize different RTAs for delay absorption for the MD80, as taken from Figure 3.4. This MD80 curve could be brought closer to the optimal FMS curve by changing the parameters used to characterize this profile within CTAS. Thus, these results are an artifact of this particular CTAS speed profile.

If potential savings were limited to flights which absorbed delays over 15 seconds (6 percent of all delays) the resulting savings are much closer to the original estimate of $200 per day. In sum, this exercise identified a fuelburn sensitivity to changes in MD80 nominal descent speeds, but the potential gain was insufficient to justify higher potential benefit numbers for this EDX mechanism.

Results Summary

This chapter evaluated EDX FMS descent speed profile benefits. The FMS downlink of its preferred altitude-speed profile to meet an arrival/departure fix crossing time allows more fuel efficient climbs/descents while maintaining DST airport capacity enhancements. The downlinked preferences would enhance DST-calculated altitude-speed profiles, saving aircraft fuel or direct operating cost in descent. Relative to the Active Baseline, it was found that EDX saved 3 lbs of fuel or $0.27 per rush arrival, with a total savings of $1.1M annually assuming NAS-wide deployment at 37-airports. This does not include the benefits of EDX1 and EDX2, assumed to be part of the Baseline.

To achieve these benefits, it is assumed that EDA can compute speed changes to increment the metering fix RTA by 5 or 10 sec, and that the associated speed changes incorporating FMS speed preferences, are provided by the controller in an accurate and timely way.

This analysis would benefit from more complete set of fleet-wide fuelburn models, rather than using just the two aircraft types that were extrapolated fleet-wide. Additionally, a more realistic FMS model would incorporate existing FMS RTA trajectory modeling algorithms and account for operational constraints and variations in wind and aircraft weight.

Table 3.4 EDX FMS Speed Profile Benefits

Airport	Annual Airport Ops (000s)	Apt Delay Delays/Category		Rush Arrival Rate*	Annual Cost Saving ($000s, 1998) EDX6
Atlanta (ATL)	773	23.88	3	30.4	63.3
Nashville (BNA)	226	1.36	5	18.2	7.9
Boston (BOS)	463	0.73	2	18.2	11.1
Bradley (BDL)	161	26.37	5	34.9	43.6
Baltimore (BWI)	270	3.67	5	18.2	13.3
Cleveland (CLE)	291	4.68	5	18.2	14.3
Charlotte (CLT)	457	6.55	4	24.3	30.0
Cincinnati (CVG)	394	10.38	4	24.3	25.8
Washington National (DCA)	310	6.53	4	24.3	20.3
Denver (DEN)	454	1.90	5	18.2	22.3
Dallas – Ft. Worth (DFW)	870	19.59	3	30.4	71.3
Detroit (DTW)	531	9.10	4	24.3	34.8
Newark (EWR)	443	65.25	1	39.5	47.2
Ft. Lauderdale (FLL)	236	1.53	5	18.2	11.6
Houston Hobby (HOU)	252	2.57	5	18.2	12.4
Washington Dulles (IAD)	330	6.81	4	24.3	21.7
Houston–Intercontinental (IAH)	392	11.45	4	24.3	25.7
N.Y. Kennedy (JFK)	361	29.53	2	34.9	34.0
Las Vegas (LAS)	480	3.68	5	18.2	23.6
Los Angeles (LAX)	764	24.13	3	30.4	62.6
N.Y. LaGuardia (LGA)	343	46.22	1	39.5	36.5
Orlando (MCO)	342	4.59	5	18.2	16.8
Chicago Midway (MDW)	254	6.70	4	24.3	16.7
Memphis (MEM)	364	NA	5	18.2	17.9
Miami (MIA)	546	6.79	4	24.3	35.8
Minneapolis (MSP)	484	9.29	4	24.3	31.7
Oakland (OAK)	516	NA	5	18.2	25.4
Chicago O'Hare (ORD)	909	34.46	2	34.9	85.7
Portland (PDX)	306	2.41	5	18.2	15.0
Philadelphia (PHL)	406	17.95	3	30.4	33.3
Phoenix (PHX)	544	7.25	4	24.3	35.7
Pittsburgh (PIT)	447	6.60	4	24.3	29.3
San Diego (SAN)	244	3.31	5	18.2	12.0
Seattle (SEA)	398	6.37	4	24.3	26.1
San Francisco (SFO)	442	56.57	1	39.5	47.1
Salt Lake City (SLC)	374	3.53	5	18.2	18.4
St. Louis (STL)	517	34.04	2	34.9	48.8
37-Airport Total/Average	430	---		---	1,129

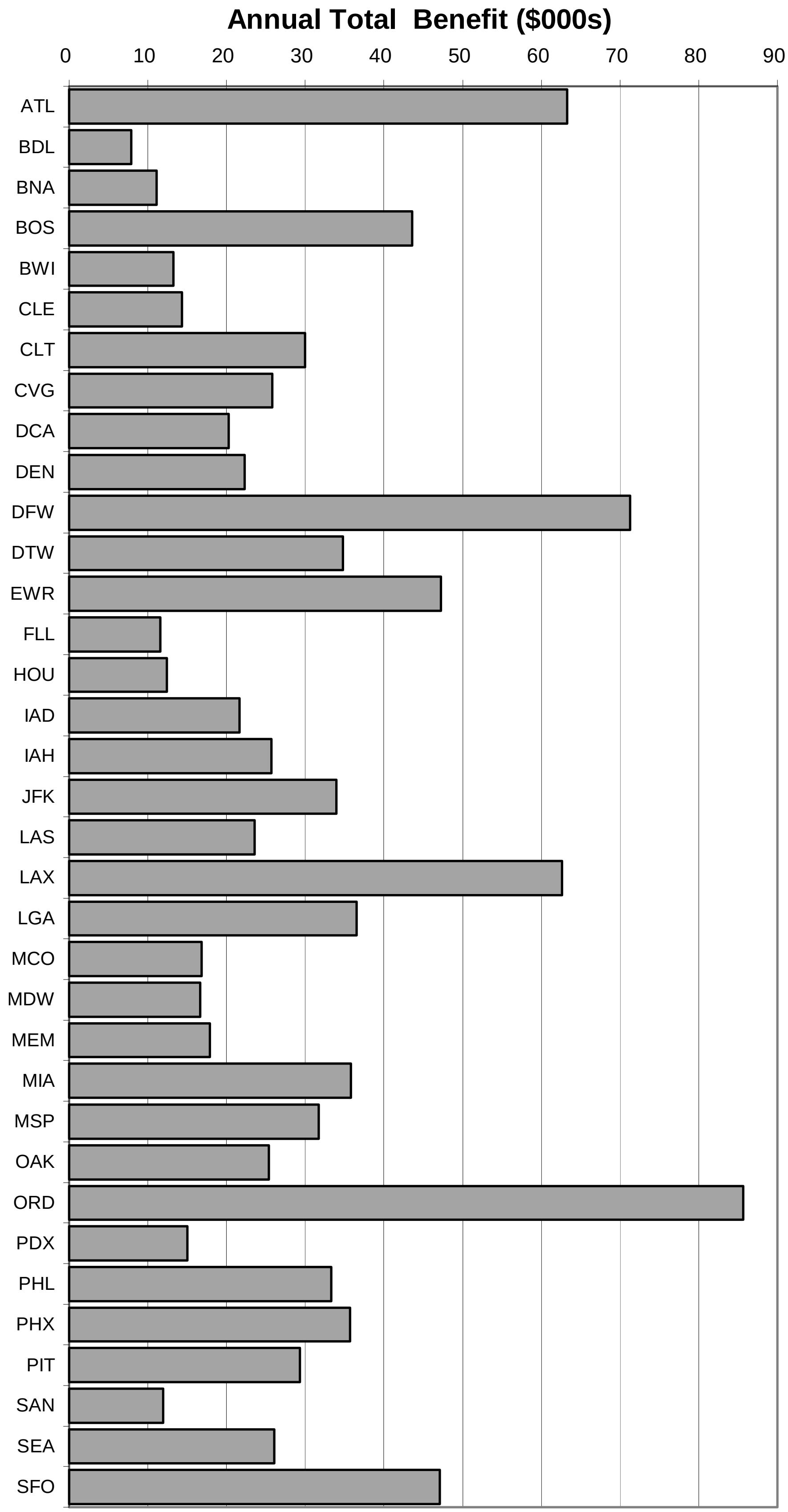


Figure 3.8 EDX FMS Speed Profile Benefits

4 Separation Assurance Benefits

Air traffic controllers deviate flights from the users' preferred trajectory, to avert impending traffic conflicts and to conform to flow-rate restrictions. The efficiency and effectiveness of such controller-imposed deviations directly affect controller and flight crew workload as well as user costs. ATM en route DSTs and their further enhancement with data exchange have the potential to reduce unnecessary deviations and improve the efficiency with which necessary deviations are implemented by more accurately predicting flight trajectories and supporting useful clearance decisions. We refer to these processes that the ATM system uses to interrupt the normal traffic flow in order to mechanize flow-rate conformance and separation assurance conflict resolution as "ATM interruptions," and the DST processes of reducing and imposing more efficient traffic interruptions as "ATM interruption benefits." This chapter evaluates EDA improvement to separation assurance flight interruptions with the EDX improvement to trajectory prediction accuracy on conflict probe DSTs. An initial EDX enhancement to flow-rate conformance interruptions was addressed in the previous chapter, FMS Descent Speed Profile Benefits, expected additional benefits have not yet been evaluated.

ATM relies on accurate predictions of future flight positions within conflict probe DSTs to accurately identify and alert them of the location and nature of potential conflicts. Within a conflict probe, trajectory prediction capabilities determine whether ATM would perceive a predicted future encounter (i.e., predicted point of closest approach between two aircraft being less than some standard separation distance) as a conflict requiring intervention. This includes ATM/DST's ability to correctly infer the potential conflict, including its timing (conflict start) and severity (minimum separation of the event). It also includes the controller's use of excess spacing buffers (that the controller uses to effect an extra margin of safety), beyond the FAA minimum aircraft protected airspace zone (PAZ) constraint, imposed to account for such conflict uncertainties.

With data exchange reduction in trajectory prediction uncertainties, controllers can become confident in the consistency of more accurate conflict predictions, and PAZ buffers can be assumed to shrink while maintaining the current level of safety in both the horizontal and vertical dimensions. Indeed, current operations impose significant vertical PAZ buffers around aircraft in climb and descent phases of flight due to limitations in ATM knowledge of aircraft state, intent, and aircraft climb/descent performance during the transition flight maneuvers. With a reduction in both horizontal and vertical buffers, ATM would less frequently perceive aircraft to be in conflict, resulting in fewer ATM flight interventions, and associated conflict resolution fuel and workload penalties [4, 41-42]. The downlink of aircraft/FMS horizontal route intent data, in particular, could significantly reduce conflict probe prediction inaccuracies. Incorrect knowledge of route intent, such as not knowing that a flight is being expedited (e.g. direct routing) and/or delayed to meet airport or flow rate constraints without filing a flight plan amendment, can lead to incorrect or inaccurate DST conflict predictions and increased false and missed alert rates. Finally, improved DST conflict prediction will include more accurate estimation of conflicting aircraft geometry and speeds, which may lead to more efficient resolution maneuvers.

This chapter summarizes ATM interruption benefits expected with data exchange, as derived in previous efforts [10, 12-13]. These benefits accrue due to more accurate conflict alerts and improved controller confidence, leading to reduced (e.g., fewer false alerts) and more efficient (e.g., fewer missed alerts) ATM interruptions of user preferred trajectories.

Analysis Process

The benefits methodology process employed in previous research [13] is described below. The sequence of analytical formulations and computer-based modelings follows the Figure S-2 approach (and numbering) of the introduction summary section. After identifying the technologies and their parametric effects of the study case (1), the Trajectory Prediction & Accuracy Model (2) uses Baseline and EDX defined data parameter accuracies to calculate the expected position error in CTAS' conflict probe prediction. This timing error is then converted into ATM perception values of miss distances and associated spacing buffers, that would be imposed by air traffic controllers to limit separation minima violations.

These modeled controller spacing buffers, defined for Baseline and EDX cases, are then combined with a DFW daily traffic schedule in an ATM Interruptions model (3). As shown in Figure 4.1, the separation assurance ATM interruption modeling components initially identify and record conflicts and near-conflicts from the metered (delayed) traffic scenario (output from the metering conformance model) in a conflict incident database. Near-conflicts are included to allow the analysis of false alerts. These incidents are then filtered through an ATM perception model to identify whether ATM would perceive the incident as a conflict requiring resolution. This perception model reflects the level of conflict probe accuracy as derived from the Trajectory Prediction & Accuracy Model (3).

A resolution is identified for each separation assurance ATM interruption and is tabulated over the daily simulation. The simulated daily interruption rates and resolution costs are then extrapolated to annual and NAS-wide levels using the economic modeling (4). These model components are discussed in more depth with the analysis results in the next section.

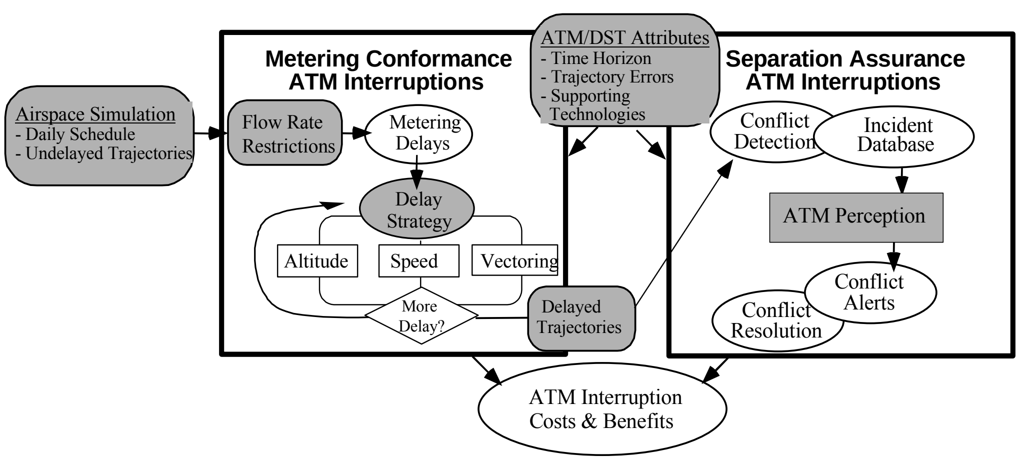


Figure 4.1 ATM Interruptions Model Approach

Study Cases

The analysis process is initiated by identifying the various candidate data exchange technologies, and their capabilities that may be associated with EDX Separation Assurance ATM Interruptions benefits. The EDX cases evaluated under this benefit mechanism include EDX1 through EDX3 and EDX5 relative to an Active Baseline. Each case improves on the trajectory prediction accuracy of various flight modes (i.e., climb, cruise, descent). All cases assume 100% FMS equipage and data exchange participation.

- **Active Baseline** – TMA/EDA
- **EDX1** – **Weather (wind & temperature)** Data Exchange
- **EDX2** – Weather, **Aircraft Weight, Thrust/Drag Coefficients** Data Exchange
- **EDX3** – Weather, Weight, Thrust/Drag, **Arrival/Departure Speed Intent** Data Exchange
- **EDX5** – Weather, Weight, Thrust/Drag, Speed Intent, **Next Two Waypoints Intent** Data Exchange

Conflict Detection

Initially a set of air-traffic “demand” trajectories for a typical day within a block of Center airspace was defined. In this study, the Fort Worth Air Route Traffic Control Center (ZFW) airspace was analyzed, including the same arrival, departure, and overflight traffic operations as discussed in Chapter 3, Center/TRACON Delay distribution [33], representing what each flight would do if left alone to fly the user’s preferred trajectory. EDA was also assumed to enable direct routing to the arrival-metering fix. Arrival flights assume EDA enabled direct routes to the metering fix and both arrival and departure trajectories were modified to impose delays necessary to meet TMA arrival schedule. These trajectories, shown in Figure 4.2 define the conflict probe traffic scenario. Departure delays were absorbed on the ground, as ground holds. Arrival delays to meet constraints were absorbed en route by speed control, altitude, and/or vectoring maneuvers.

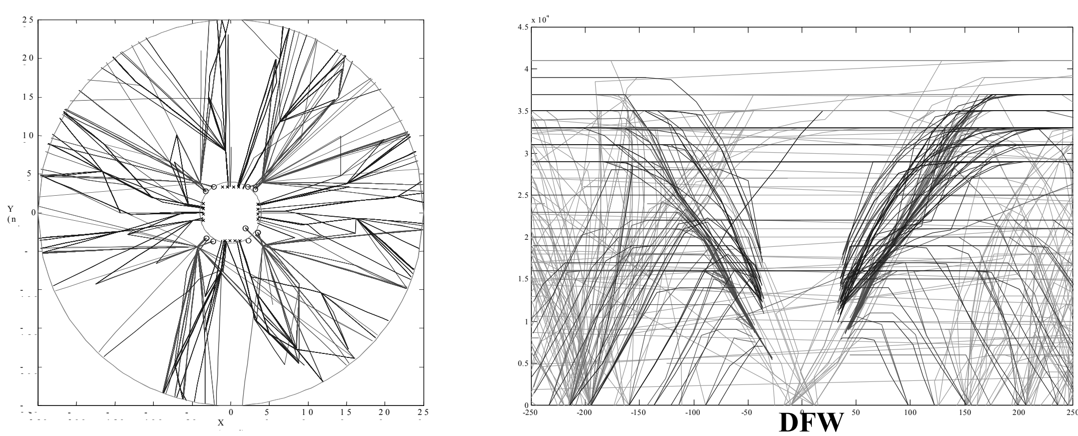


Figure 4.2 Plan and Profile View of DFW Study Day Operations

A conflict detection algorithm was used to identify actual and potential conflicts that would occur without ATM intervention (referred to as "incidents"). From the trajectory simulation, all potential conflict pairs were identified using a stepping algorithm, which uses inputs of trajectory data and Protected Airspace Zone (PAZ) bounds. In creating the incident database, a PAZ larger than the minimum FAA separation requirement was assumed to allow a margin of safety imposed by controllers as well as to facilitate analysis of false alerts. An "conflict" is identified if an aircraft enters the PAZ of another aircraft. The resulting Incident Database identifies all aircraft pairs that could be perceived by ATM as requiring intervention. The database also identifies information about the conflict including the separation at the point of closest approach.

ATM Perception of Conflict

ATM is assumed to intervene and alter conflicting trajectories that are perceived by the operating conflict probe tool to violate Acceptable Controller Spacing (or the controller's PAZ). With improved perception, fewer incidents will be perceived as requiring intervention. ATM perception of conflict is characterized by four metrics that vary with data exchange scenario and phase of flight:

- Trajectory Prediction Accuracy
- Acceptable Controller Spacing
- Perceived Miss Distance
- Probability of Perceived Conflict

Each of these metrics affecting perception of conflict is defined below.

Trajectory Prediction Accuracy is defined as a combination of position and velocity error terms that are combined as a function of the time horizon used for the particular study case. The process of computing trajectory accuracy, whether it is represented as timing error or position error at a fixed point in time, is developed in Appendix B. This includes calibration of descent metering fix timing error resulting from the application of EDA [20] field observations.

Table 4.1 shows the resultant trajectory prediction error in climb, cruise, and descent segments as combined for arrival, overflight and departure flight operations. These categories represent the flight phase of the aircraft at the conflict point of closest approach (PCA). A 12-minute time horizon was chosen to represent all cases. Note that shading of a cell in Table 4.1 indicates improvement with implementation of the successive EDX cases.

Table 4.1 Assumed ATM Trajectory Prediction Accuracy

	DEP		OVR	ARR	
	CL	CR	CR	CR	D
12-minute Trajectory Prediction Accuracy (nm)					
Active Baseline	13.8	4.7	4.7	3.7	1.6
EDX1 (Weather)	13.7	4.7	4.6	3.6*	1.4*
EDX2 (Aircraft Weight)	12.2	4.7	4.6	3.6*	1.4*
EDX3 (Speed Intent)	9.4	3.6	3.6	3.6*	1.4*

* Applies to metered arrivals only.

Acceptable Controller Spacing indicates at what separation values (lateral and vertical miss distances) ATM controllers would perceive a projected encounter as a conflict requiring intervention. These are functions of the required minimum separation and an intentional excess spacing buffer. This buffer is used by controllers to prevent violation of the FAA separation minima in the presence of uncertainties. This concept is displayed in Figure 4.3 for the lateral dimension. As trajectory uncertainties are reduced and controllers become confident in the consistency of more accurate trajectory predictions, this buffer is assumed to shrink, while maintaining the current level of safety.

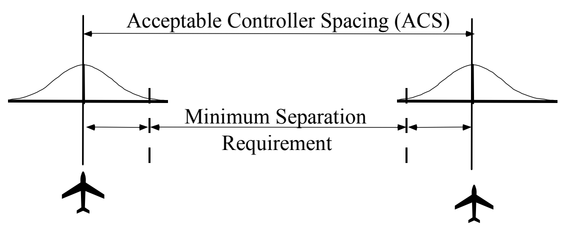


Figure 4.3 Acceptable Controller Spacing (ACS) Results from Predicted Position Accuracy.

To be in conflict, aircraft must violate Acceptable Controller Spacing (ACS) in either the lateral or vertical dimensions. ACS is assumed to be dependant upon position accuracy. Equation (4.1) is used to relate position accuracy to horizontal and vertical ACS. The minimum separation fraction values for each flight mode are estimated based on current system operations [47].[3]

$$ACS = n\sigma_{p.pred} + Rule \tag{4.1}$$

where: $Rule$ = En route minimum separation requirement [46]
= 5 nm horizontally, 2000/1000 ft vertically >FL290/≤FL290
$\sigma_{p.pred}$ = Trajectory prediction position accuracy (Table 4.1)
n = Minimum separation fraction
= (0.22, 0.67, 0.60) horizontal and (72.5, 0.0, 200.0) vertical for (climb, cruise, descent) flight segments

[3] That is the observed current system ACS values [47] are combined with current system trajectory prediction position accuracy values [13] and FAA minimum en route separation (*Rule*) to derive the minimum separation coefficient (*n*). Using this minimum separation fraction, the ACS values for this study (Table 4.3) are generated reflecting Table 4.2 EDA/EDX trajectory prediction position accuracies.

Using Equation (4.1), Table 4.2 shows the baseline and improvement in ACS assumed with the EDX cases. Again, shaded cells show improvement due to data exchange when compared to the previous case. Note that the vertical ACS does not improve, since they are already at the FAA minimums.

Table 4.2 Acceptable Controller Spacing

	Horizontal ACS (nm)					Vertical ACS (ft)**				
	DEP		OVR	ARR*		DEP		OVR	ARR*	
	CL	CR	CR	CR	D	CL	CR	CR	CR	D
Acceptable Controller Spacing (ACS)										
Active Baseline	8.00	8.00	8.00	7.37	6.07	3000 2000	2000 1000	2000 1000	2000 1000	2357 1357
EDX1 (Weather)	7.98	7.91	7.91	7.26	5.95	2994 1994	2000 1000	2000 1000	2000 1000	2318 1318
EDX2 (Aircraft Weight)	7.66	7.91	7.91	7.26	5.91	2886 1886	2000 1000	2000 1000	2000 1000	2303 1303
EDX3 (Speed Intent)	7.04	7.26	7.26	7.26	5.91	2680 1680	2000 1000	2000 1000	2000 1000	2303 1303

* Applies to metered arrivals only.
** Upper/Lower values refer to above/below FL290.

Perceived Miss Distance indicates the accuracy to which ATM perceives the extent and degree of the potential conflict. Inaccurate perception may lead to false or missed interventions because the conflict may be perceived as more or less severe than in actuality. This concept is illustrated in Figure 4.4 where actual aircraft tracks and miss distance (r_f) are shown with bold (—) lines. Dashed (--) lines show inaccurately predicted flight tracks due to ATM prediction errors in heading and speed. These errors result is a range of perceived conflict miss distances which may be more or less severe than the actual miss distance.

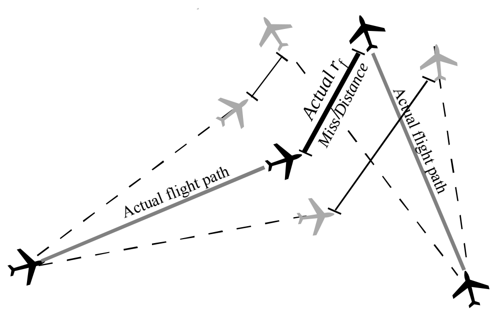


Figure 4.4 Perceived Miss Distance results from Actual Miss Distance and Trajectory Prediction Accuracy.

Equation (4.2) describes the variation in miss distance at point of closest approach as a function of the technology-specific trajectory prediction accuracies of the conflicting aircraft pair:

$$\sigma_{r_f} = \sqrt{\sigma^2_{p,pred,aci} + \sigma^2_{p,pred,acj}} \tag{4.2}$$

where: $\sigma_{p,pred,\,acx}$ = Predicted trajectory position accuracy at point of closest approach for aircraft *x* (nm)

For each incident in the Incident Database, the flight mode of each aircraft at the conflict point of closest approach (PCA) is identified. The associated 12-minute trajectory prediction accuracies (prior to conflict start), drawn from Table 4.1, are used in Equation (4.2) to define ATM perception miss distance error. The result is a Gaussian distribution of miss distance for each conflict under each technology case. The mean value of this distribution is equivalent to the actual uninterrupted Incident Database miss distance. The miss distance distribution is compared with ACS to determining the ATM's probability of perceived conflict and subsequent intervention.

A *Probability of Conflict,* or probability of ATM interruption, is calculated by comparing the ACS with the conflict probe perceived attributes and actual Incident Database attributes for each incident. This probability indicates the likelihood that a controller would perceive the incident as a conflict requiring intervention. Because the perceived miss distance is stochastic in nature, it takes the form of a Gaussian distribution, as shown in Figure 4.5, with a mean value equal to the actual miss distance. The ACS bounds (±ACS) are overlaid onto the perceived miss distance curves. The shaded region between ±ACS is the probability that ATM would perceive this incident as equal or less than the ACS, and intervene to resolve the perceived conflict. The unshaded region represents the probability that no conflict was perceived nor intervention made at the strategic conflict probe time horizon.

Figure 4.5 shows three curves representing three possible outcomes, the actual miss distance is: *(i)* less than the minimum separation requirement (±M); *(ii)* larger than minimum but less than the ACS (±ACS); or *(iii)* larger than the ACS. Because ATM perception is not completely accurate, intervention or lack of intervention may be an incorrect action. In general, ATM interruptions fall into three categories: correct, missed, and false alerts, defined as:

- **Correct Alert** (CA) - Conflicts correctly perceived by ATM (i.e., minimum aircraft separation falls below the Acceptable Controller Spacing). As a result of correct perception, ATM is able to resolve the impending conflict at the strategic time horizon.
- **Missed Alert** (MA) - Conflicts *not* correctly perceived by ATM. Due to conflict probe inaccuracies, the tool identified no projected conflict. As a result of ATM misperception, conflict detection, and the initiation of a conflict resolution maneuver, will be delayed resulting in a tactical resolution and economic penalty.
- **False Alert** (FA) - Erroneous conflicts detected by the conflict probe tool despite an acceptable miss distance. False alerts result in extra workload, for controllers and pilots, and add additional flight costs for deviations that are not necessary.

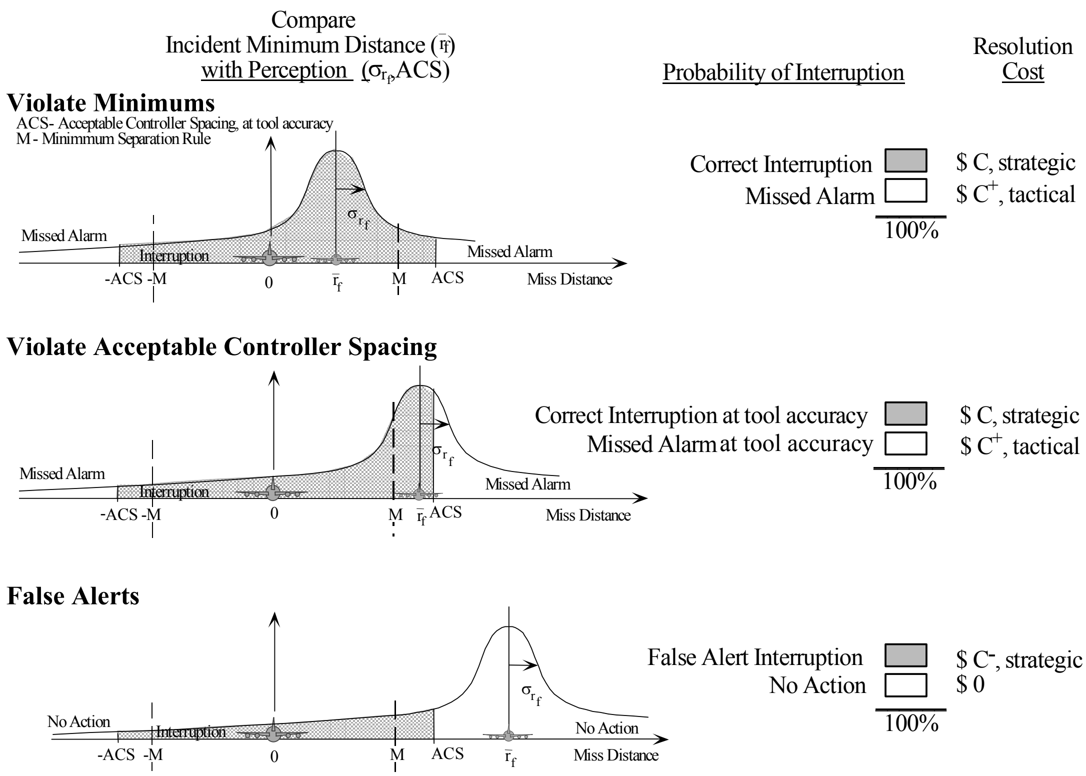


Figure 4.5 Comparison of Perceived Miss Distance Curves and Acceptable Controller Spacing (ACS) results in Probability of Conflict and Resolution Costs for Each Type of Incident

In Figure 4.5, intervention is the correct course of action in the top two scenarios because the actual miss distance (between aircraft symbols) is less than the ACS. In these cases, a missed alert would result if no 12-min.ute intervention were made. Once ATM *did* perceive these incidents, a tactical intervention would be required with a shorter time horizon at a higher cost. Conversely, intervention in the last scenario of Figure 4.5 would be a false alert, and would lead to an unnecessary ATM interruption and its associated costs. Improved accuracy of the conflict probe tool would lead to a tightening of the Perceived Miss Distance curve about the mean value. As a result, the shaded region would be modified, reducing the number of false and missed alerts.

The probability of perceived conflict, which determines the likelihood of ATM interruption of an incident, is equivalent to the area under the perceived miss distance curve between ±ACS, calculated using Equation (4.3):

$$P(conflict) = \frac{1}{2} erf\left(\frac{ACS + r_f}{\sqrt{2}\sigma_{r_f}}\right) + \frac{1}{2} erf\left(\frac{ACS - r_f}{\sqrt{2}\sigma_{r_f}}\right) \tag{4.3}$$

where: r_f = Actual miss distance at point of closest approach

ACS = Acceptable controller spacing (ACS)

σ_{r_f} = Miss distance error from Equation (4.2)

$erf(x)$ = integral of the standardized Gaussian distribution function from(0, x)

$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-u^2} du$ and $\frac{1}{2} erf\left(\frac{x}{\sqrt{2}}\right)$ = integral of the normal probability distribution function

This probability determines the likelihood of ATM interruption of this incident.

Impact of Off Flight Plan/Incorrect Intent

In the current system, flights are frequently diverted off the filed flight plan for a variety of reasons including metering conformance, conflict avoidance, and accommodation of requests for direct routes. If these deviations are not recorded as a flight path amendment, CTAS is unaware of the changed aircraft intent. The lack of updated intent degrades conflict probe trajectory prediction, frequently resulting in a false alert for the original conflict, and/or a missed alert on the new route. Future integrated conflict probe, direct routing, and metering conformance tools will assist controllers in recording these intent changes. Alternatively, aircraft downlink of its next few waypoints (i.e., the EDX5 case) can correct CTAS aircraft intent errors. In both cases, the improved knowledge of aircraft intent leads to conflict probe performance benefits.

Figure 4.6 illustrates a situation where an eastbound aircraft's filed flight plan route supposedly conflicts with a southeast flight (actually a false alarm). To avoid this, the controller vectors the eastbound aircraft for spacing conformance but fails to record this change as a flight plan amendment. As a result, the initial presumed conflict is avoided (false alert), but is replaced by a new undetected conflict (missed alert) with a second southeast flight.

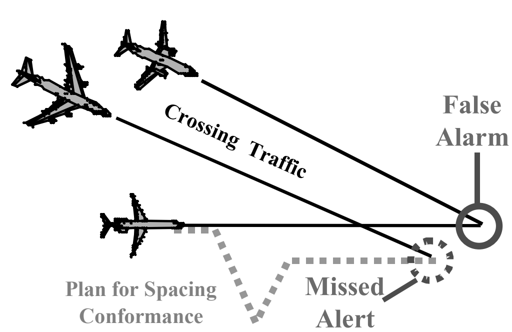


Figure 4.6 Off-flight Plan Effect on ATM Perception

The analysis accounted for inaccurate intent information as part of ATM perception. If an aircraft is off its filed flight plan, the inaccurate intent data changes the ATM perception attributes of Figure 4.5 slightly, as shown in Figure 4.7. The key change is the shift of the second aircraft's actual location, reflecting a gap between the perceived (flight plan) and actual (off flight plan) miss distance. Thus, the perceived miss distance curve is still centered about the flight plan intent, which no longer matches the actual intent of the aircraft. Per the scenario of Figure 4.7, inaccurate intent results in a significantly higher probability for the indicated false alert than would occur with good intent information.

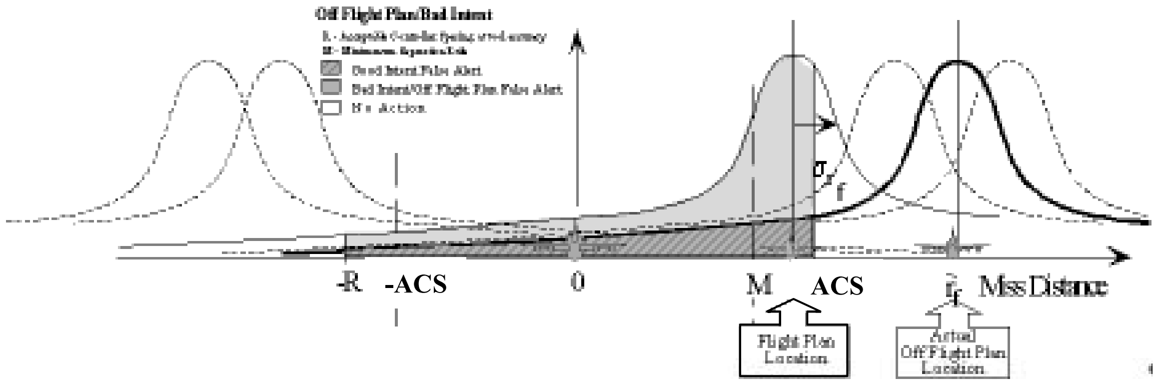


Figure 4.7 Off-Flight-Plan Probability of Conflict Estimation

For this study, it is assumed that a controller would clear the aircraft to a route that would avoid any original flight plan-based conflict, while not creating any new conflicts. This approach implies that the off-flight plan route would avoid the flight-plan-based conflict, converting it to a false alert. The off-flight plan location of the second aircraft was assumed to be outside the ACS (±R) by a distance equal to the horizontal ACS safety buffer (ACS – FAA minimum Rule). This results in the solid off-flight plan curve of Figure 4.7 (regardless of the original miss distance attributes). Thus, under erroneous intent, ATM's perceived probability of conflict would not change, implied by the area under the original FP-based location between the ACS bounds, but it would now represent a false alert, as the off-flight plan route avoided the conflict and thus no intervention is necessary.

Using this approach, a lack of accurate intent data will result in a higher frequency of false alerts. Probability of conflict is calculated for both accurate and inaccurate intent situations and combined based on the weighted frequency of inaccurate intent information.

The frequency of aircraft off-flight plan intent errors is assumed to vary by case, as shown in Table 4.3. In the Passive Baseline, full intent errors are assumed in all flight modes, reflecting the lack of integration of the metering (TMA) and the conflict probe tools and no downlinked aircraft intent. The frequency of inaccurate intent was assumed to be 15% for all flight modes, based on discussions with conflict probe experts [47] and Indianapolis Center observations that only 18% of all route clearances are documented [48]. With the integration of arrival metering/conflict probe in the EDA case, metered arrival intent errors are assumed to be removed, while non-metered arrivals, departures, and overflight intent inaccuracy remains unchanged. Under EDX5, the aircraft is assumed to automatically downlink the next two waypoints, improving intent for all flights. Thus, EDX5 is assumed to remove aircraft intent errors on all flight modes.

Table 4.3 Frequency of Off-Flight-Plan Route Intent Error

	Units	Active Baseline and EDX1, EDX2, EDX3					EDX5				
		DEP		OVR	ARR*		DEP		OVR	ARR	
		CL	CR	CR	CR	D	CL	CR	CR	CR	D
Off Flight Plan Route Intent Error Frequency											
Inaccurate Intent	%	15%	15%	15%	0%	0%	0%	0%	0%	0%	0%
Accurate Intent	%	85%	85%	85%	100%	100%	100%	100%	100%	100%	100%

* Applies to metered arrivals only.

Conflict Resolution

For each perceived conflict recorded in the Incident Database, a resolution cost was defined. This fuel cost penalty represents the cost just to avert a conflict, at the given time horizon. ATM shaded (interrupt) and unshaded (no interrupt) action probabilities of Figure 4.5 and 4.7 are tied to resolution costs, resulting in a weighted resolution cost for each conflict or predicted conflict. The costs of the shaded and unshaded actions are conceptually noted in Figure 4.5. In general, correct alerts incur a resolution cost initiated at the technology's strategic time horizon. Missed alerts incur a more expensive resolution cost, initiated at a shorter time horizon (i.e., 5 minutes). False alerts were assigned a small cost related to resolving a non-conflict that would not actually have occurred.

The conflict resolutions are achieved with heading changes, sensitive to conflict geometry and severity, with the resolution maneuver split between the involved aircraft. The trajectories were not changed to implement the ATM intervention action; rather, the intervention was used to identify a representative cost penalty for the interruption. Three types of ATM intervention costs were identified: correct, false, and missed alerts. As previously discussed, the resolution cost of each type differs in its time horizon and conflict severity.

The resolution maneuver includes heading changes and steady level flight segment components. Conflict resolutions from altitude or speed changes were not examined. The fuel costs of executing these flight segments were summed and compared to the fuel costs of uninterrupted flight. For all maneuvers, the resolution of the conflict resulted in an increase in path distance with constant speed. The change in path distance was converted to a time value based on the aircraft speed, multiplied by a fuelburn rate (per unit time), and a baseline cost of fuel ($0.10/lb). The fuelburn rates were based on Eurocontrol's BADA performance data [38], sensitive to altitude, flight mode (climb, cruise, and descent), and aircraft class.

Economic Analysis

The number and cost of Separation Assurance ATM Interruptions were tallied for each scenario by applying the ATM resolution strategies to conflicts, as perceived by ATM. The probability of conflict, based on scenario-specific ATM perception, was used to weight the overall interruption cost for each incident of the Incident Database. Fuel costs for resolving all ATM perceived conflicts from the 24-hour incident database were tabulated. By comparing the costs of changes in ATM interruptions to a baseline system, expected daily fuel cost savings were identified.

Table 4.4 summarizes the number and type of ATM perceived conflicts simulated under each scenario, categorized as correct (CA), missed (MA), and false (FA) alerts Each conflict implies interrupting one or both flights to maintain separation. These ATM interruptions resolve conflicts between aircraft pairs of various types including DFW arrivals (ARR), DFW departures (DEP), and overflights (OVR, including satellite airport operations) within the DFW en route/transition airspace. Arrival-Arrival and Departure-Departure alerts with PCAs larger than the FAA minimum separation rule (5 nm) were not included (NAs in Table 4.4). Because controllers closely monitor these streams at tight in-trail spacing during rush periods (assumed to be 5.5 nm for this study), conflict alerts between these aircraft can be a nuisance [47]. Additionally, it should be noted that although EDA metering conformance maneuver advisories are designed to be conflict-free, where possible with all other traffic, this de-confliction was not fully accounted for in the modeling of EDA trajectories in the Baseline case. As comparison of the scenarios in Table 4.4 shows, the total number of conflicts declines with EDX enhancement, a reduction of almost 10 percent (187 conflicts) in EDX5. Additionally, the number of false and missed alert conflicts decline, particularly the missed alerts. For example, in all cases, the number of unavoidable conflicts where the point of closest approach (PCA) separation is less than the FAA minima (PCA < Rule), remains relatively constant, with increased share of correct vs. missed alerts. In contrast, conflicts above FAA minimums but below Acceptable Controller Spacing (Rule<PCA<ACS) decline with the EDX reductions in ACS safety buffers. Rather than shift to a correct alert, these conflicts seem to become false alerts. Improved cases should allow false alerts to be averted, but additional false alerts may result from the reduction in ACS.

Table 4.4 Number and Category of Separation Assurance Conflicts

	Number of ATM Resolutions						Metrics	
	PCA< Rule		Rule<PCA<ACS		PCA>ACS			
	CA	MA	CA	MA	FA	Total	R_{MA}	R_{FA}
Active Baseline								
OVR-OVR	131	77	156	159	259	782	45%	50%
OVR-ARR	67	30	94	82	120	392	41%	44%
OVR-DEP	48	35	79	93	161	416	50%	63%
ARR-DEP	15	19	34	50	76	195	58%	65%
DEP-DEP	18	20	NA	NA	NA	37	NA	NA
ARR-ARR	142	25	NA	NA	NA	167	NA	NA
Total	421	205	364	383	617	1,989	47%	53%
EDX1 (Weather)								
OVR-OVR	132	76	152	154	259	773	45%	50%
OVR-ARR	67	29	92	80	117	386	41%	44%
OVR-DEP	48	34	79	92	161	414	50%	63%
ARR-DEP	15	19	34	49	76	193	58%	66%
DEP-DEP	18	19	NA	NA	NA	37	NA	NA
ARR-ARR	144	23	NA	NA	NA	167	NA	NA
Total	425	200	357	375	613	1,971	46%	54%
EDX2 (Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	135	73	150	139	259	756	43%	52%
OVR-ARR	68	28	91	74	117	379	39%	45%
OVR-DEP	50	33	79	86	161	409	48%	65%
ARR-DEP	16	18	33	42	76	185	55%	70%
DEP-DEP	19	19	NA	NA	NA	37	NA	NA
ARR-ARR	144	23	NA	NA	NA	167	NA	NA
Total	432	194	353	342	613	1,934	45%	55%
EDX3 (Speed Intent, Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	145	64	141	110	253	713	38%	55%
OVR-ARR	71	25	82	58	117	354	35%	50%
OVR-DEP	54	29	75	67	157	382	43%	70%
ARR-DEP	18	16	32	34	76	175	50%	76%
DEP-DEP	21	16	NA	NA	NA	37	NA	NA
ARR-ARR	145	23	NA	NA	NA	167	NA	NA
Total	454	172	330	269	604	1,829	40%	60%
EDX5 (Next 2 Waypoints, Speed Intent, Weight, Thrust/Drag Coefficients, Weather)								
OVR-OVR	145	64	141	110	234	694	38%	51%
OVR-ARR	71	25	82	58	117	354	35%	50%
OVR-DEP	54	29	75	67	150	375	43%	67%
ARR-DEP	18	16	32	34	75	175	50%	76%
DEP-DEP	21	16	NA	NA	NA	37	NA	NA
ARR-ARR	145	23	NA	NA	NA	167	NA	NA
Total	454	172	330	269	577	1,802	40%	57%

Note: Number of false alerts was assumed to be equal or less than prior case.
PCA = Point of Closest Approach distance, Rule = FAA minima, ACS = Acceptable Controller Spacing
ARR = DFW Arrival, DEP = DFW Departure, OVR = Overflight / Satellite

The number of missed alerts declines by 25 percent, with the largest benefits resulting from the ACS improvements of aircraft weight (EDX2) and speed intent (EDX3). The false alerts decline by almost 2 percent through EDX3 and by an additional 5 percent with the EDX5 downlink of the next two waypoints. Because these improvements may not keep up with the reduction in overall conflicts, the benefit is less apparent from the missed and false alert rate metrics (R_{MA} and R_{FA}), where the false alert actually increase as a proportion of overall conflicts.

Table 4.5 summarizes the number of EDX separation assurance interruptions and the associated average and daily resolution costs from the DFW simulation. The interruption rate is based on the interruptions per 8,003 total daily operations (arrival, departure and overflight) in the simulation. Note that only fuel costs were tabulated in the horizontal vectoring resolution maneuvers.

Table 4.5 DFW Separation Assurance Conflict Rates and Costs

	Interrupted Conflicts		Resolution Cost	
	Number	Rate/100	($/op)	($/day)
Active Baseline	1,989	24.9	$1.79	$3,552
EDX1 (Weather)	1,971	24.6	$1.77	$3,482
EDX2 (Aircraft Weight)	1,934	24.2	$1.74	$3,374
EDX3 (Speed Intent)	1,829	22.9	$1.58	$2,882
EDX5 (Next Two Waypoints)	1,802	22.5	$1.58*	$2,830

* EDX3 cost rates applied to EDX5.

As with other benefit mechanisms in this report, these daily DFW savings were extrapolated to an annual NAS-wide level by accounting for the total number of 1996 operations at each facility. As in other chapters, the simple extrapolation employs Equations (4.4) and (4.5) to estimate benefits.

$$\text{Annual Cost} = (\text{Annual Ops}) \times (\text{Interrupt Rate}) \times (\text{Cost Per Interrupt}) \quad (4.4)$$
$$\text{Annual Savings} = \text{Annual Cost}_{BL} - \text{Annual Cost}_{EDX} \quad (4.5)$$

where: *Annual Ops* = Annual ARTCC operations (00s) (Appendix C)
Interrupt Rate = Number of interruptions per 100 ARTCC operations (Table 4.5)
Cost Per Interrupt = Average cost per interruption (Table 4.5)

The interruption rates and costs observed in the daily simulation and used in Equation (4.4) are included in Table 4.5. The annual ARTCC operations [49] and annual savings by airport are shown in Table 4.6. The annual savings are plotted graphically by airport in Figure 4.8. The total EDX5 benefits at any one ARTCC ranges from $125,000 at ZOA to $264,000 at ZAU, with all 37 airports having an annual benefit of $3.6 million under EDX5. The primary benefit resulted from the EDX5 waypoint intent (44 percent) and EDX3 speed intent (40 percent), which impacted all flight modes. EDX2 aircraft weight (12 percent) and EDX1 weather (4 percent) resulted in smaller share of the overall savings. Note that these results are highly sensitive to the order in which these incremental improvements were made.

It should be noted that the estimates do not account for the significant controller workload benefits. Controller workload is enhanced by EDX improving conflict probe trajectory prediction accuracy, through better knowledge of actual aircraft state, weather and atmospheric conditions, and future intent. The improved trajectory prediction, especially the EDX5 downlink of next two waypoint intent, greatly reduces the probability of missed alerts or nuisance (false) alerts. Indeed, the analysis identified a 25 percent reduction in the number of missed and a 7 percent reduction in false alerts under EDX, in addition to a 10 percent reduction in overall detected conflicts. Safety also benefits with enhanced surveillance under improved EDX trajectory prediction capabilities.

Results Summary

This chapter evaluated EDX separation assurance ATM interruption benefits. ATM relies on accurate predictions of flight trajectories within its conflict probe tool to accurately identify the location and nature of potential separation assurance violations. With more accurate EDX arrival trajectory predictions ATM would less frequently perceive aircraft to be incorrectly or out of conflict (missed and false alerts), resulting in fewer ATM flight interventions and associated resolution fuel penalties. Additionally, improved conflict prediction will include more accurate estimation of conflict geometry and speeds, leading to more efficient resolution maneuvers.

Relative to an Active Baseline, it was found that EDX reduced separation assurance interruptions by 10 percent with each interruption savings an average of 2 lbs or $0.21, for a total savings of $3.6M annually assuming NAS-wide deployment at 37-airports. More significantly, the EDX separation assurance conflicts required less overall workload primarily because of the integration with metering conformance flight intent, reducing the number of missed and false alerts by 25 and 7 percent, respectively, with an overall reduction in conflicts of 10 percent. As a result, EDA enhances overall safety, strategic controller planning across multiple sectors, and reduces nuisance conflict alerts.

It should be noted that the simple off-flight plan inaccurate intent modeling methodology employed in this analysis does not assess flight-specific route changes, nor evaluate the impact on missed alerts. These benefit estimates are sensitive to ARTCC traffic routing complexity. A typical day of ZFW Center activity was analyzed with interrupt rates and per operation savings extrapolated to other airports. The NAS-wide EDX benefit estimates would be enhanced with more comprehensive evaluation of the en route traffic routing of various facilities.

Table 4.6 EDX Separation Assurance Benefits

Airport	ARTCC	Annual ARTCC Ops (000s)	Annual Savings ($000s, 1998) EDX1	EDX2	EDX3	EDX5
Atlanta (ATL)	ZTL	2,453	22.0	59.8	205.5	224.1
Nashville (BNA)	ZBW	1,727	15.5	42.1	144.7	157.8
Boston (BOS)	ZME	1,978	17.7	48.2	165.7	180.7
Bradley (BDL)	ZBW	1,727	15.5	42.1	144.7	157.8
Baltimore (BWI)	ZDC	2,331	20.9	56.8	195.3	213.0
Cleveland (CLE)	ZOB	2,870	25.7	70.0	240.5	262.2
Charlotte (CLT)	ZTL	2,453	22.0	59.8	205.5	224.1
Cincinnati (CVG)	ZID	2,222	19.9	54.2	186.1	203.0
Washington National (DCA)	ZDC	2,331	20.9	56.8	195.3	213.0
Denver (DEN)	ZDV	1,527	13.7	37.2	128.0	139.5
Dallas – Ft. Worth (DFW)	ZFW	2,118	19.0	51.6	177.4	193.5
Detroit (DTW)	ZOB	2,870	25.7	70.0	240.5	262.2
Newark (EWR)	ZNY	2,040	18.3	49.7	170.9	186.4
Ft. Lauderdale (FLL)	ZMA	1,542	13.8	37.6	129.2	140.9
Houston Hobby (HOU)	ZHU	1,853	16.6	45.2	155.2	169.3
Washington Dulles (IAD)	ZDC	2,331	20.9	56.8	195.3	213.0
Houston–Intercontinental (IAH)	ZHU	1,853	16.6	45.2	155.2	169.3
N.Y. Kennedy (JFK)	ZNY	2,040	18.3	49.7	170.9	186.4
Las Vegas (LAS)	ZLA	1,981	17.7	48.3	165.9	181.0
Los Angeles (LAX)	ZLA	1,981	17.7	48.3	165.9	181.0
N.Y. LaGuardia (LGA)	ZNY	2,040	18.3	49.7	170.9	186.4
Orlando (MCO)	ZJX	1,878	16.8	45.8	157.4	171.6
Chicago Midway (MDW)	ZAU	2,894	25.9	70.6	242.5	264.4
Memphis (MEM)	ZME	1,978	17.7	48.2	165.7	180.7
Miami (MIA)	ZMA	1,542	13.8	37.6	129.2	140.9
Minneapolis (MSP)	ZMP	2,027	18.1	49.4	169.9	185.2
Oakland (OAK)	ZOA	1,368	12.2	33.4	114.6	125.0
Chicago O'Hare (ORD)	ZAU	2,894	25.9	70.6	242.5	264.4
Portland (PDX)	ZSE	1,393	12.5	34.0	116.7	127.2
Philadelphia (PHL)	ZNY	2,040	18.3	49.7	170.9	186.4
Phoenix (PHX)	ZAB	1,505	13.5	36.7	126.1	137.5
Pittsburgh (PIT)	ZOB	2,870	25.7	70.0	240.5	262.2
San Diego (SAN)	ZLA	1,981	17.7	48.3	165.9	181.0
Seattle (SEA)	ZSE	1,393	12.5	34.0	116.7	127.2
San Francisco (SFO)	ZOA	1,368	12.2	33.4	114.6	125.0
Salt Lake City (SLC)	ZLC	1,509	13.5	36.8	126.4	137.9
St. Louis (STL)	ZKC	1,986	17.8	48.4	166.4	181.5
37-Airport Total/Average	---	39,202	350.9	955.9	3,284.4	3,581.6

* Totals include only one instance of each ARTCC, excluding the shaded ARTCC operations separation assurance operations.

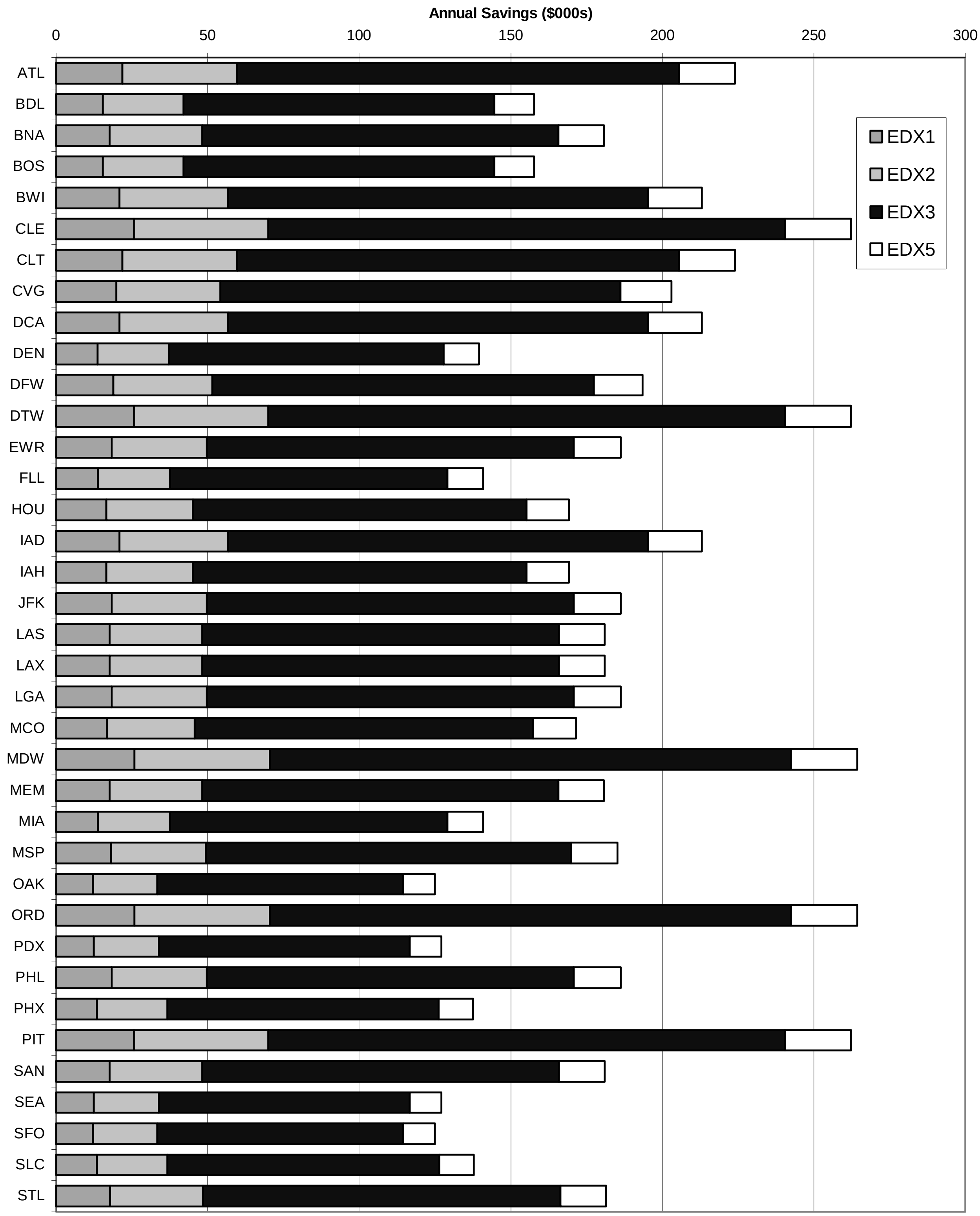


Figure 4.8 EDX Separation Assurance Benefits

5 Departure Direct Routing Benefits

Air traffic management automation tools, such as the CTAS EDA Direct-to Tool (D2), assist controllers in accommodating user requests for more direct routing. These tools incorporate meteorological conditions (e.g., winds) to assess whether the direct route would save fuel, and they facilitate the flight plan amendment process to execute the direct route clearance. Controllers frequently employ direct routes to resolve conflicts. However, controllers will typically not employ direct routing if it creates a new conflict. The identification of new conflicts is dependant upon ATM perception of separation and the buffers placed on the minimum aircraft protected airspace zone (PAZ). As discussed with conflict probe modeling of the previous chapter, increased trajectory prediction accuracy with data exchange is expected to reduce the PAZ buffers, leading to fewer perceived conflicts. As a result, more Direct-To advisories may be employed saving both aircraft time and fuel. Although this benefit is applicable to both non-metered arrivals and departures, this analysis addresses only departures.

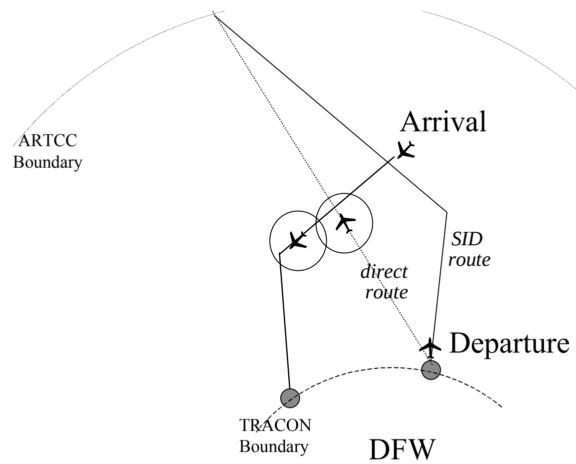


Figure 5.1 Conflict with Arrival Bars Departure Direct Routing

Figure 5.1 illustrates a situation where a departure is barred from the direct route because of a conflict with an arrival. The Standard Instrument Departure (SID) route is followed instead because of the procedural separation it provides. However, if the aircraft PAZs, shown as circles around the aircraft at conflict, were reduced with improved EDX trajectory prediction accuracy, this may no longer be considered a conflict, enabling the departure to fly the direct route.

Analysis Process

The benefits methodology process is an extension of the incident database created in the ATM interruptions analysis of the previous chapter. The overall sequence of analytical formulations and computer-based modelings follows the Figure S.2 approach (and numbering) of the introduction summary section. Initially DST technology definitions for baseline and EDX cases are defined (1). ATM criteria to enable direct route departures (2) with data exchange are specified. The fuel saving of direct routing is also identified.

When the criteria are applied to a daily traffic scenario of conflicts (3), the frequency of enabling direct route departures with EDX and the associated per operation fuel and time cost savings are estimated. The resulting DFW daily fuel savings are then extrapolated to annual and NAS-wide levels (4). These model components are discussed in more depth with the analysis results in the following sections.

For each simulated departure, the fuel savings of direct route operations were identified. Direct routing allows an aircraft to improve flight efficiency by altering the horizontal-plane motion of the aircraft trajectory. Currently, a typical terminal-area departure path exiting a TRACON includes a specified SID route. Direct routing shortens the actual path length flown by "cutting the corner" and flying directly to an en route waypoint on the ARTCC boundary.

Study Cases

The analysis process is initiated by identifying the various candidate DST technologies, and their capabilities, that may be associated with EDX Enabled Departure Direct Routing benefits. The EDX cases evaluated under this benefit mechanism include EDX3 relative to a Passive Baseline and two versions of the Active Baseline. Both the Standard Terminal Arrival Route (STAR) and direct route arrival versions of the Active Baseline are included to better understand the variability in the results. The EDX3 case improves trajectory prediction accuracy of all flight modes allowing (a) a reduced protected airspace zone (PAZ); and (b) more enabled direct flights when no additional conflicts are created. All cases assume 100% FMS equipage and data exchange participation.

The cases studied were:

- **Passive Baseline** – TMA, assuming SID and STAR routing as in other chapters
- **Active Baseline with STAR** – TMA/EDA, assuming EDA <u>does not</u> enable arrival direct routing
- **Active Baseline with direct arrivals** – TMA/EDA, assuming EDA enabled arrival direct routing, as in other chapters. Departure routes remain on standard instrument departure (SID) routes.
- **EDX3 with both direct arrivals and departures** – Weather, Weight, Thrust/Drag, Arrival/Departure Speed Intent Data Exchange

Conflict Incident Database

This analysis uses the conflict incident databases from Chapter 4, Separation Assurance Benefits. Initially an en route set of air-traffic "demand" trajectories for a typical day within a block of en route airspace, defined in this study as the Fort Worth Air Route Traffic Control Center (ZFW) airspace, were simulated. This set of trajectories included arrival, departure, and overflight traffic operations [33], as shown in Figure 5.2.

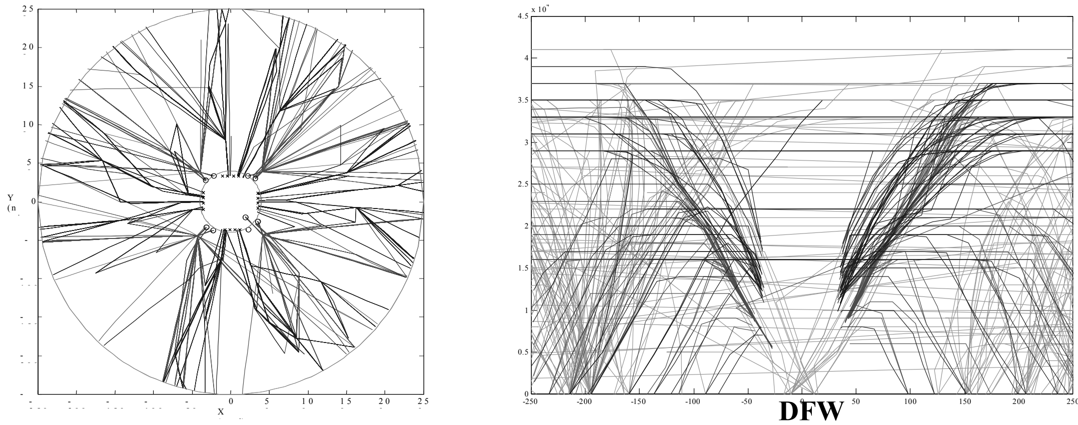


Figure 5.2 Plan and Profile View of DFW Study Day Operations

The only modification to the user's preferred trajectory were flight maneuvers necessary to delay the DFW arrival and departure aircraft, in order to meet airport and arrival/departure metering fix flow-rate restrictions, shown in Table 5.1. Departure delays were absorbed on the ground, as ground holds. Arrival delays were absorbed en route by a mix of speed control, altitude, and/or vectoring maneuvers, assumed to reflect EDA metering conformance advisories. The EDA part of the Active Baseline was assumed to enable direct routing to the arrival-metering fix for the Active Baseline cases. These trajectories define the conflict probe traffic scenarios.

Table 5.1 DFW Scheduling Criteria

Scheduling Criteria	Assumed Value
Minimum Arrival Meter-Fix Separation	5.50 nm
Maximum TRACON Arrival Rate (4 Arrival Runways)	150 ac/hr
Maximum TRACON Departure Rate (3 Departure Runways)	115 ac/hr

A conflict detection algorithm was used to identify actual conflicts that would occur without ATM intervention. From the trajectory simulation, all conflict pairs were identified using a stepping algorithm, which required inputs of trajectory flight data and Protected Airspace Zone (PAZ) bounds. A PAZ envelopes each aircraft, allowing adequate safety buffers to prevent violation of the FAA separation minima in the presence of uncertainties. The bounds of the PAZ are interpreted as the horizontal and vertical acceptable controller spacing (ACS), as shown in Figure 5.3. Conflicts occur if an aircraft enters the PAZ (or equivalently violates the ACS bounds) of another aircraft, requiring ATM interruption. (The previous chapter includes conflicts in the incident database with a PAZ larger than the acceptable controller spacing (ACS) to include a controller spacing buffer and to account for false alerts; these conflicts were not considered in this analysis.)

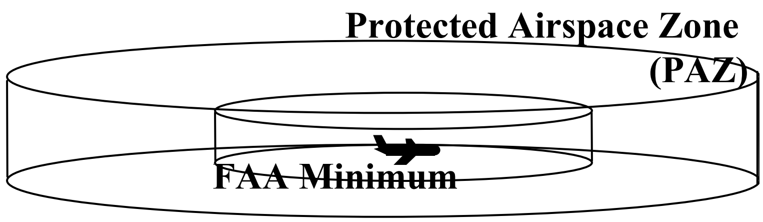


Figure 5.3 Protected Airspace Zone (PAZ) Exceeds FAA Separation Minima

As defined previously, ACS (and thus the PAZ bounds) is assumed to be a function of the required minimum separation [46] and an intentional excess spacing buffer. As trajectory uncertainties are reduced and controllers become confident in the consistency of more accurate trajectory predictions, this buffer is assumed to shrink, while maintaining the current level of safety. The assumed ACS values previously derived in Chapter 4 are shown in Table 5.2. The Passive Baseline ACS values are assumed to represent current system operations [47], with the subsequent reductions based on improved trajectory prediction accuracy, as discussed in Chapter 4.

Table 5.2 Acceptable Controller Spacing

		Passive Baseline (TMA)					Active Baseline (EDA)					EDX1-EDX3				
		DEP		OVR	ARR*		DEP		OVR	ARR		DEP		OVR	ARR	
	Units	CL	CR	CR	CR	D	CL	CR	CR	CR	D	CL	CR	CR	CR	D
Horizontal ACS																
En Route	nm	8.00	8.00	8.00	7.37	6.07	8.00	8.00	8.00	7.37	6.07	7.04	7.26	7.26	7.26	5.91
Vertical ACS																
>FL290	Ft	3000	2000	2000	2000	2357	3000	2000	2000	2000	2357	2680	2000	2000	2000	2303
<=FL290	Ft	2000	1000	1000	1000	1357	2000	1000	1000	1000	1357	1680	1000	1000	1000	1303

Note: FAA en route separation minima are 5 nm and 2000/1000 ft above/at-below FL290.
* Applies to metered arrivals only.

An incident database representing each study case was employed in the analysis to identify the frequency of EDX enabled direct departure routes. Table 5.3 summarizes the databases criteria used. It should be noted that EDX3 is assumed to include the benefits of the EDX1 (wind/temperature) and EDX2 (aircraft weight and thrust/drag coefficients) data exchanges. Additionally, an alternate Active Baseline is included to evaluate the impact of STAR vs. direct arrival routes on the ability to enable direct departure routes.

Table 5.3 Conflict Database Criteria

Case	ACS	Departure Routing	Arrival Routing
Passive Baseline	TMA	SID	STAR
Active Baseline, STAR Arrivals*	EDA	SID	STAR
Active Baseline, Direct Arrivals	EDA	SID	Direct
EDX1-EDX3	EDX3	Direct	Direct

* Alternate Active Baseline

Direct Route Fuel Savings

The potential benefit of direct routing varies with the number of segments, or "dog legs," in the nominal baseline SID route. Figure 5.4 illustrates the horizontal-path differences between trajectories flying SID and direct departure routes from DFW. In converting the SID routes to direct routes, the departure metering fix crossing times (inner ring in Figure 5.4) were held constant.

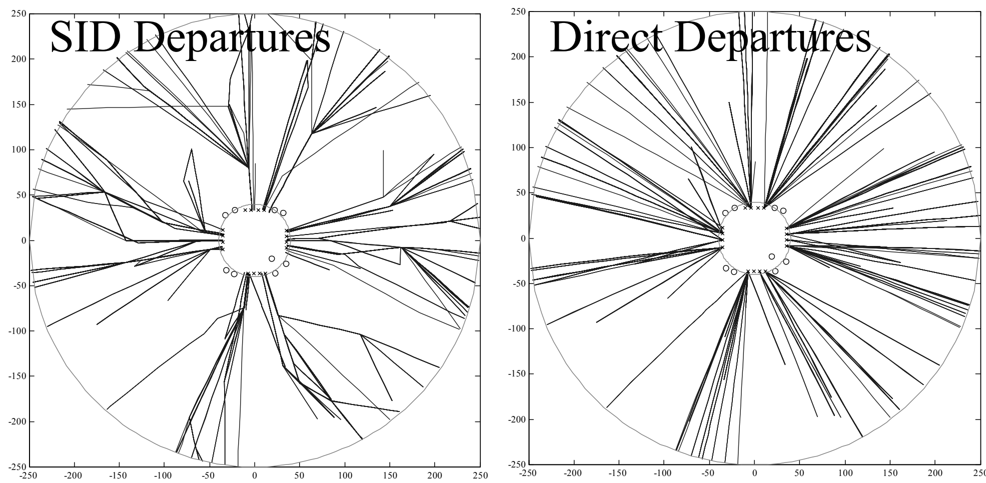


Figure 5.4 Plan View DFW En Route SID vs. Direct Departure Trajectories

Benefits analysis involved a comparison of the fuel burned along both the SID and direct departure route(DIR). Both fuel and time savings were evaluated using Equation (5.1).

$$DIRSavings = (Time_{\mathrm{SID}} - Time_{\mathrm{DIR}}) \times [Cost_{\mathrm{Time}} + (FuelRate \times FSF \times Cost_{\mathrm{Fuel}})] \quad (5.1)$$

where:
- $Time_{\mathrm{i}}$ = Departure fix to ARTCC exit flight time for SID and direct (DIR) routings
- $Cost_{\mathrm{Time}}$ = FAA-based time cost rate by aircraft class (Appendix C)
- *FuelRate* = B737 Cruise fuelburn rate at top-of-climb speed and altitude (Appendix E)
- *FSF* = Fuel Scale Factor (FSF), FAA-based airborne fuel cost rates by aircraft class, relative to B737 aircraft class (Appendix C)
- $Cost_{\mathrm{Fuel}}$ = \$0.10 per lb of fuel

The fuelburn rates employ cruise fuelburn rates from a high-fidelity B737 aircraft simulation [14, 50], as used in Chapter 3, Descent Speed Profile Negotiation, combined with FAA-based fuel scale factors [38].

The range of departure direct route savings using Equation (5.1) are shown in Figure 5.5. On average, time savings were 1.12 minutes costing $17.67, with fuel savings of 82 lbs costing $8.17. Time savings comprise approximately two-thirds of the total savings. The particular direct-route savings enabled by EDX are pulled from this set.

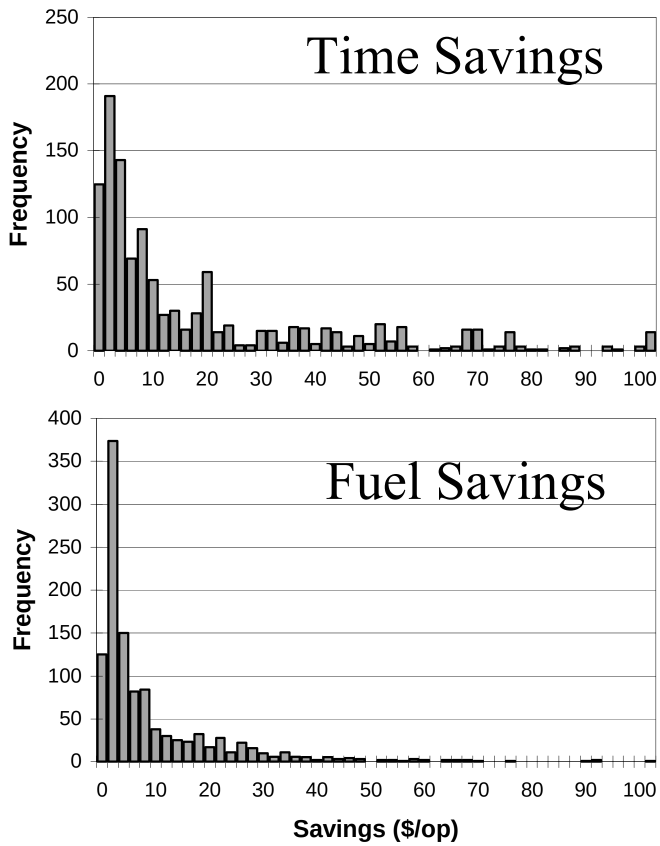


Figure 5.5 Departure Direct Route Time and Fuel Cost Saving Distribution

Enabled Direct Departures

For each departure operation the number of conflicts over the course of the flight was identified from the incident databases identified above. EDX was assumed to enable a direct route for any departure if the EDX direct route eliminated all conflicts for that flight. If no conflicts existed in the baseline case, no benefit accrued, assuming direct routes would be enabled in baseline operations. Of 1,134 simulated departures, the number of departure flights satisfying these criteria, are shown in Table 5.4. EDX enabled 6 to 13 percent of the departures to fly a conflict-free direct route. This represented 20-24 percent of those not enabled in the baseline. The number of additional EDX direct routes was largest under the Active Baseline (STAR routes). However, the other baselines appear to enable significantly more direct route prior to EDX. The key differences between the Passive and Active Baselines with STAR arrivals, is the different metering conformance maneuvers under TMA and EDA operations and reduced PAZ around EDA metered arrival flights, due to enhanced arrival trajectory prediction.

Table 5.4 Frequency of Enabled Direct Departures

	Passive Baseline (STAR Arrivals)	Active Baseline (STAR Arrivals)	Active Baseline (Direct Arrivals)
Baseline Enabled Direct Routes	841 (74%)	530 (47%)	803 (71%)
+ EDX Enabled Direct Routes	71 (6%)	146 (13%)	68 (6%)
Total Direct Departure Routes	912 (80%)	676 (60%)	871 (77%)

Economic Analysis

The EDX enabled direct-route operations and their associated cost savings were combined to arrive at an estimate of daily savings, as summarized in Table 5.5. Note that the number of EDX enabled direct routes varies depending upon which of the three baseline cases is assumed. The savings vary due to the different set of enabled routes under each case.

Table 5.5 DFW EDX Direct Departure Savings

	Passive Baseline (STAR Arrivals)	Active Baseline (STAR Arrivals)	Active Baseline (Direct Arrivals)
Number of Impacted Departure Operations	71	146	68
Enabled Rate (per 100 Airport Operations)	32.55	66.94	31.18
Average Savings Per Operation	1.03 min/op	1.20 min/op	1.03 min/op
	78 lbs/op	81 lbs/op	90 lbs/op
	$24.12/op	$25.74/op	$27.09/op
Daily Fuel Savings	$1,713	$3,758	$1,842

As with other benefit mechanisms in this report, these daily DFW savings were extrapolated to an annual NAS-wide level by accounting for the total number of 1996 operations at each facility. As in other chapters, the simple extrapolation employs Equation (5.2) to estimate benefits.

$$\textit{Annual Savings} = (\textit{Annual Ops}) \times (\textit{Rush Arrivals}_{DFW}) \times (\textit{Apt Factor}) \times (\textit{Savings Per Interrupt}) \quad (5.2)$$

where: *Annual Ops* = Annual Airport operations (00s) (Appendix C)
Rush Arrivals$_{DFW}$ = DFW number of rush arrivals per 100 daily airport operations (Table 5.5)
Apt Factor = Factor accounting for local airport rush arrival frequency relative to DFW, based on FAA delay data (Appendix C)
Savings Per Interrupt = Average cost savings per rush arrival (Table 5.5)

As in the other evaluations, DFW rush arrival rates were adjusted by an *Airport Factor* to account for variations in congestion at each facility. Airports with less overall delays are assumed to require disproportionately fewer metering conformance actions. Thus, airports with less demand-capacity congestion are assumed to delay fewer en route arrival and departure aircraft to meet airport-scheduling constraints. An individual airport's assumed delayed arrival rates is adjusted from the nominal DFW value of Table 5.5, using FAA delay data [35]. These data record delays at each airport in excess of 15 minutes in CY1996, including both arrivals and departures. This metric hides the significant number of smaller delays during an arrival rush period and includes delayed departures, making it a gross indicator of the airport's level of delayed arrival flights. Despite these limitations, this data provided a reasonable factor for extrapolating the detailed DFW traffic analyses to the 37-NAS airports. To do so, the NAS airports were broken into five delay categories. Engineering judgement was used to assign each category a rush arrival rate relative to DFW. Simulated rates [13] of 130%, 115%, 100%, 80%, and 60% for airport delay classes 1, 2, 3, 4, and 5, were used as shown in Table 5.6. The FAA delay data and criteria used to assign delay classes are included in Appendix C.

Table 5.5 gives the enabled frequency and average savings per enabled direct route used in the annual extrapolation of Equation (5.2). Note that the frequency is given per daily airport operation, which includes both arrivals and departures. The savings include both time and fuel costs, based on FAA crew and maintenance time cost rates in Appendix C and $0.10 per pound of fuel.

The annual savings by airport are shown in Table 5.6. The annual savings are also plotted graphically by airport in Figure 5.6. The airports with high annual operations gained the most, including ORD, DFW, ATL, and LAX each saving over $0.6M annually.

The total EDX benefit varied significantly depending upon the baseline. The Active Baseline benefits proved larger than Passive Baseline benefits, with the Active Baseline STAR arrivals having significantly higher benefits than the direct arrivals case. As previously shown in Table 5.4, both the Passive Baseline and Active Baseline-Direct Arrivals case, without EDX, are able to enable 70 percent of the departure direct routes without conflict. Because the Active STAR Baseline only enabled 47 percent prior to EDX, EDX provides more benefit. Overall, when accounting for both baseline and EDX enabled direct routing, 80 percent of the departures flew direct under the passive STAR Baseline, 77 percent with the Active Direct baseline, and 60 percent with Active STAR Baseline. However, one should not conclude that to maximize departure routing it is best to retain STAR approaches. Indeed, all flights should be enabled to fly direct routings, which may require additional conflict resolution, such as altitude separation, to fully enable this preferred state. Since the direct arrivals case is more consistent with the Active Baseline assumed in other studies, these benefits ($13.4M annually) are included in the benefits summary at the beginning of the report. Additionally, it should be noted that this EDX benefit mechanism would also apply to non-metered arrival flights, a topic for future analysis.

Results Summary

This chapter evaluated EDX enabled direct departure benefits. ATM automation tools assist controllers in accommodating user requests for more direct routing. These tools assess whether the direct route would save fuel, and facilitates the flight plan amendment process to execute the direct route clearance. Controllers frequently employ direct routes to resolve conflicts. However, controllers will typically not employ direct routing if it creates a new conflict. The identification of new conflicts is dependant upon ATM perception of closest point spacing between crossing paths and the buffers placed on the required minimum separation (currently 5 miles lateral spacing and 1000/2000 ft in altitude below/above FL290). Increased trajectory prediction accuracy with data exchange is expected to reduce the buffers that controllers will use, leading to fewer perceived conflicts. As a result, more direct routes may be employed saving aircraft time and fuel. More benefits were expected under the Active Baseline. Relative to a Passive Baseline, it was found that EDX enabled 8 percent more departure direct routes, with an average savings of 78 lbs and 1.03 minutes or $24.12 per operation, for a total savings of $5.0M annually assuming NAS-wide deployment at 37-airports. Active Baseline benefits enabled roughly the same number of direct departures, but showed slightly more fuel savings, with an average savings of 90 lbs and 1.03 minutes or $27.09 per operation, for a total savings of $5.4M annually NAS-wide.

This first-cut analysis shows significant benefits for EDX. It should be evaluated using higher-fidelity airspace model to confirm these benefits, as well as assess the extension of EDX improvements to non-metered arrival direct routes.

Table 5.6 EDX Enabled Departure Direct Route Benefits

Airport	Annual Airport Ops (000s)	Apt Delay Delays/Category		Rush Arrival Rate	EDX1-EDX3 Annual Cost Savings ($000s, 1998) Passive Baseline (STAR Arrivals)	Active Baseline (STAR Arrivals)	Active Baseline (Direct Arrivals)
Atlanta (ATL)	773	23.88	3	30.4	606.7	1,331.2	652.5
Nashville (BNA)	226	1.36	5	18.2	126.2	277.0	135.8
Boston (BOS)	463	0.73	2	18.2	177.7	389.9	191.1
Bradley (BDL)	161	26.37	5	34.9	363.2	796.9	390.6
Baltimore (BWI)	270	3.67	5	18.2	212.1	465.5	228.2
Cleveland (CLE)	291	4.68	5	18.2	228.5	501.5	245.8
Charlotte (CLT)	457	6.55	4	24.3	358.9	787.5	386.0
Cincinnati (CVG)	394	10.38	4	24.3	309.0	678.1	332.3
Washington National (DCA)	310	6.53	4	24.3	243.2	533.7	261.6
Denver (DEN)	454	1.90	5	18.2	356.7	782.7	383.6
Dallas – Ft. Worth (DFW)	870	19.59	3	30.4	683.1	1,498.8	734.6
Detroit (DTW)	531	9.10	4	24.3	417.1	915.1	448.5
Newark (EWR)	443	65.25	1	39.5	348.2	764.0	374.5
Ft. Lauderdale (FLL)	236	1.53	5	18.2	185.6	407.2	199.6
Houston Hobby (HOU)	252	2.57	5	18.2	198.1	434.6	213.0
Washington Dulles (IAD)	330	6.81	4	24.3	259.5	569.4	279.1
Houston–Intercontinental (IAH)	392	11.45	4	24.3	307.8	675.3	331.0
N.Y. Kennedy (JFK)	361	29.53	2	34.9	283.1	621.2	304.5
Las Vegas (LAS)	480	3.68	5	18.2	376.6	826.4	405.1
Los Angeles (LAX)	764	24.13	3	30.4	600.0	1,316.4	645.2
N.Y. LaGuardia (LGA)	343	46.22	1	39.5	269.1	590.3	289.3
Orlando (MCO)	342	4.59	5	18.2	268.5	589.2	288.8
Chicago Midway (MDW)	254	6.70	4	24.3	199.7	438.3	214.8
Memphis (MEM)	364	NA	5	18.2	285.8	627.1	307.4
Miami (MIA)	546	6.79	4	24.3	429.1	941.6	461.5
Minneapolis (MSP)	484	9.29	4	24.3	379.7	833.2	408.4
Oakland (OAK)	516	NA	5	18.2	405.6	889.9	436.2
Chicago O'Hare (ORD)	909	34.46	2	34.9	714.0	1,566.6	767.8
Portland (PDX)	306	2.41	5	18.2	240.3	527.2	258.4
Philadelphia (PHL)	406	17.95	3	30.4	318.9	699.8	343.0
Phoenix (PHX)	544	7.25	4	24.3	427.5	938.0	459.7
Pittsburgh (PIT)	447	6.60	4	24.3	351.4	771.0	377.9
San Diego (SAN)	244	3.31	5	18.2	191.3	419.7	205.7
Seattle (SEA)	398	6.37	4	24.3	312.2	685.1	335.8
San Francisco (SFO)	442	56.57	1	39.5	347.3	762.1	373.5
Salt Lake City (SLC)	374	3.53	5	18.2	293.6	644.1	315.7
St. Louis (STL)	517	34.04	2	34.9	406.3	891.4	436.9
37-Airport Total/Average	430	---		---	12,482	27,387	13,423

Figure 5.6 EDX Enabled Departure Direct Routing Benefits

6. Conclusions/Recommendations

This report identifies the potential benefits of various EDX benefit mechanisms relative to common FFP1 Baseline assumptions. As noted earlier, these analyses are summarized and extended from a number of previous efforts, which involve many assumptions, varying levels of analysis fidelity, and very limited technical and operational assessment. Key findings of the individual EDX benefit mechanism including analysis assumptions and limitations are discussed, followed by specific recommendations for improving the analyses. Other recommendations can be found in the respective reference reports of each chapter.

Conclusions

Airport Throughput

Reduced runway threshold crossing separations between consecutive pairs of landing aircraft (in excess of minimums) are expected from EDX as a result of improved arrival metering fix delivery accuracy. The reduced variance in arrival metering fix crossing times leads to reduced runway gaps with associated airport throughput increases and aircraft delay and delay propagation reduction, especially during rush periods. EDX enhancements to the Passive Baseline saved the most. EDX2 and EDX3 Passive Baseline operations saved an average 0.70 seconds of delay or $0.26 per operation (time and fuel), for a total NAS-wide deployment at 37-airports of 49.5 hours and $4.8M annually. EDX1 and EDX2 Active Baseline operations saved 0.19 seconds of delay or $0.07 per operation, for a total NAS-wide deployment at 37-airports of 13.4 hours and $1.3M annually.

These benefits reflect a reduction in the average runway threshold excess spacing buffer. A rough indication of the benefits to DST (EDA, TMA, and pFAST) throughput can be made by noting the airport delay savings in Figure 1.4. These are approximately 1-2 second TMA buffer improvement, 4 second pFAST improvement, 1 second EDA improvement, and this study's 0.08/0.02 second Passive/Active Baseline buffer improvement (Table 1.4).

It should also be noted that this analysis, an update of previous studies, was limited by the use of a runway demand and capacity modeling tool (AIRNET) which does not account for airspace constraints and subtleties of arrival scheduling embedded in proposed ATM DSTs. To address these limitations, Seagull has initiated development of a higher fidelity model, the Integrated Air Traffic (IAT) Model, which has been used in recent benefits assessments for TMA and EDA [30]. Additionally, there is some concern regarding the underlying schedule used to model LGA. Because of the high demand at LGA, delays are unable to dissipate, and they build-up without break over the full day. As a result, any improvement to LGA runway separation leads to significant savings. It is recommended that the IAT model be applied to refine these airport throughput benefits and the LGA flight schedule be updated to reflect existing activity.

Center/TRACON Delay Distribution

Reduced variance in EDX arrival metering fix delivery accuracy and EDX4 TRACON time-to-fly predictions, results in arrival flight efficiency benefits due to the ability to absorb delay more efficiently in Center airspace while still maintaining a given TRACON entry rate. More savings were found with the Active Baseline case, as this case was less restricted by the maximum controllability window of the various approach routes. Relative to the Passive Baseline, it was found that EDX shifted 11-20 seconds of rush arrival delay from TRACON to Center airspace. This saved an average of 12 lbs of fuel or $1.18 per rush arrival ($93 per average rush), with a total savings of $4.9M annually assuming NAS-wide deployment at 37-airports. Relative to an Active Baseline, it was found that EDX shifted 11-20 seconds of rush arrival delay from TRACON to Center airspace. This saved 14 lbs of fuel or $1.44 per rush arrival ($118 per average rush), with a total savings of $6.0M annually NAS-wide.

The EDX benefits were evaluated relative to a FFP1 Baseline, which includes TMA. A rough indication of the Center/TRACON delay distribution benefits of EDX relative to other ATM DSTs can be made by using Figure 2.2 and the arrival metering fix delivery accuracy values (1-sigma) of 180 seconds [22] prior to TMA, 90 seconds with TMA, and 15-20 seconds with EDA [20]. Note that through TMA implementation, the maximum delay absorption capability of a route (typically 100-300 seconds) would likely require a TRACON delay setting below optimal. Thus, despite TMA's significant improvement in metering fix delivery accuracy, little change would occur in the TRACON delay setting, allowing only limited shifting of delay to more fuel-efficient ARTCC airspace. Post-TMA, improvements to the metering fix accuracy, such as with EDX, enables a reduction in TRACON delay along the optimal line, resulting in significantly higher benefits per metering fix accuracy improvement.

To achieve these benefits, it is assumed that TRACON traffic management coordinators would be comfortable in shifting delay upstream (i.e., less TRACON front-loading) with the more accurate metering fix delivery schedule adherence of these DSTs. Additionally, the study would benefit from a better understanding of the controllability window (minimum/maximum TRACON delay setting) of various TRACON arrival routes at various ATM facilities.

Another key assumption driving these estimates is that aircraft fuelburn rates for absorbing delay are 1.5 times larger in TRACON relative to ARTCC airspace. This assumption should be calibrated with field data, and may differ under Passive and Active Baseline (including EDA) metering conformance delay strategies. Alternatively, higher fidelity aircraft trajectory and fleet mix models could be employed to improve fuel burn estimates.

FMS Descent Speed Intent

The FMS downlink of its preferred altitude-speed profile to meet an arrival/departure fix crossing time allows more fuel efficient climbs/descents while maintaining DST airport capacity enhancements. The downlinked preferences would enhance DST-calculated altitude-speed profiles, saving aircraft fuel or direct operating cost in descent. Relative to the Active Baseline, it was found that EDX saved 3 lbs of fuel or $0.27 per rush arrival, with a total savings of $1.1M annually assuming NAS-wide deployment at 37-airports. This does not include the benefits of EDX1 and EDX2, assumed to be part of the Baseline.

To achieve these benefits, it is assumed that EDA can compute speed changes to increment the metering fix RTA by 5 or 10 sec, and that the associated speed changes incorporating FMS speed preferences, are provided by the controller in an accurate and timely way.

This analysis would benefit from more complete set of fleet-wide fuelburn models, rather than using just the two aircraft types that were extrapolated fleet-wide. Additionally, a more realistic FMS model would incorporate existing FMS RTA trajectory modeling algorithms and account for operational constraints and variations in wind and aircraft weight.

Separation Assurance

ATM relies on accurate predictions of flight trajectories within its conflict probe tool to accurately identify the location and nature of potential separation assurance violations. With more accurate EDX arrival trajectory predictions ATM would less frequently perceive aircraft to be incorrectly or out of conflict (missed and false alerts), resulting in fewer ATM flight interventions and associated resolution fuel penalties. Additionally, improved conflict prediction will include more accurate estimation of conflict geometry and speeds, leading to more efficient resolution maneuvers.

Relative to an Active Baseline, it was found that EDX reduced separation assurance interruptions by 10 percent with each interruption savings an average of 2 lbs or $0.21, for a total savings of $3.6M annually assuming NAS-wide deployment at 37-airports. More significantly, the EDX separation assurance conflicts required less overall workload primarily because of the integration with metering conformance flight intent, reducing the number of missed and false alerts by 25 and 7 percent, respectively, with an overall reduction in conflicts of 10 percent. As a result, EDA enhances overall safety, strategic controller planning across multiple sectors, and reduces nuisance conflict alerts.

It should be noted that the simple off-flight plan inaccurate intent modeling methodology employed in this analysis does not assess flight-specific route changes, nor evaluate the impact on missed alerts. These benefit estimates are sensitive to ARTCC traffic routing complexity. A typical day of ZFW Center activity was analyzed with interrupt rates and per operation savings extrapolated to other airports. The NAS-wide EDX benefit estimates would be enhanced with more comprehensive evaluation of the en route traffic routing of various facilities.

Departure Direct Routing

ATM automation tools assist controllers in accommodating user requests for more direct routing. These tools assess whether the direct route would save fuel, and facilitates the flight plan amendment process to execute the direct route clearance. Controllers frequently employ direct routes to resolve conflicts. However, controllers will typically not employ direct routing if it creates a new conflict. The identification of new conflicts is dependant upon ATM perception of closest point spacing between crossing paths and the buffers placed on the required minimum separation (currently 5 miles lateral spacing and 1000/2000 ft in altitude below/above FL290). Increased trajectory prediction accuracy with data exchange is expected to reduce the buffers that controllers will use, leading to fewer perceived conflicts. As a result, more direct routes may be employed saving aircraft time and fuel. More benefits were expected under the Active Baseline. Relative to a Passive Baseline, it was found that EDX enabled 8 percent more departure direct routes, with an average savings of 78 lbs and 1.03 minutes or $24.12 per operation, for a total savings of $5.0M annually assuming NAS-wide deployment at 37-airports. Active Baseline benefits enabled roughly the same number of direct departures, but showed slightly more fuel savings, with an average savings of 90 lbs and 1.03 minutes or $27.09 per operation, for a total savings of $5.4M annually NAS-wide.

This first-cut analysis shows significant benefits for EDX. It should be evaluated using higher-fidelity airspace model to confirm these benefits, as well as assess the extension of EDX improvements to non-metered arrival direct routes.

Recommendations

- Expand modeling conditions and calibrate baseline with field data - The analyses in this report relied on detailed study at a limited set of airports, applying the applicability and per operation savings found at these airport facilities to estimate NAS-wide benefits. The NAS-wide estimates would clearly benefit from detailed study at more airports reflecting the range of airport-specific characteristics and constraints and their impact on applicability and per operation savings. Additionally, field data, such as that being collected by the FFP1 program office, could also be employed to calibrate the baseline case to match observed ATM performance, including the number and amount of rush arrival delays. The rush arrival rate impacts the Separation Assurance and Enabled Direct Departure benefit mechanisms.
- Continue to Develop and Employ Higher-Fidelity Scheduling Models – The EDX airport throughput analysis applies a different modeling approach than has been used for assessing other EDX benefit mechanisms and evaluating other DST improvements. Since the original throughput studies were conducted, as summarized in this report (Chapter 1). Seagull has initiated development of a higher-fidelity Integrated Air Traffic (IAT) Model. IAT addresses some of the limitations of the runway capacity model that was employed in the previous work (i.e. AIRNET). Additionally, the IAT model is set up to produce more refined Center/ TRACON Delay Distribution benefit assessments, and integrate them synergistically with the airport throughput mechanism.
- Update Assumptions with EDX Phase 2 Field Evaluation Data - The studies summarized in this report make assumptions on the accuracy of various CTAS data inputs, both with and without user-CTAS data exchange. The quantitative results of the joint NASA/FAA En Route Data Exchange Phase 2 Field Evaluation planned for Fall 2000 should provide means to estimate more accurate values for these parameters. The field data can be used to fine-tune the statistical parametric values used in Step 1 of the evaluation process described earlier, and to validate the potential benefits estimates summarized in this report.
- Review Expected Benefit to Passive DSTs - It should be noted that the Passive Baseline case benefits may be optimistic and the ability of the subtle data exchange improvements to impact the Passive Baseline advisories is unclear. The assumed Passive Baseline trajectory accuracy improvements should be reviewed with CTAS experts and the resulting benefits estimates adjusted accordingly.
- EDX1 and EDX2 benefits to FMS Descent Speed Profile – Only looked at EDX6 negotiation, assuming EDX1 and EDX2. Specific benefits of these calibration data exchanges may incur more benefit than the more complex EDX6 speed negotiation. Test with new EDX Phase 2 Field Test Data in CTAS trajectory predictions, using FMS fuel-optimal from existing analysis.
- Extend and Enhance Enabled Direct Routing Benefits - Additionally, it should be noted that this EDX benefit mechanism would also apply to non-metered arrival flights, a topic for future analysis. Additionally, alternative mechanisms to avoid conflicts could be created such as altitude separation
- Expand analysis to cover Terminal DST use of data exchange –Of the benefits mechanisms analyzed here, expected terminal DST should also benefits from Airport throughput and Center/TRACON Delay distribution. The terminal benefits may be larger than EDA benefits for these mechanisms, since the terminal DSTs are closer to the runway and thus have a larger impact on runway separation accuracy (for airport throughput) and TRACON time-to-fly estimates (for Center/TRACON delay distribution).

Acronyms

AATT	NASA’s Advanced Air Transportation Technologies project
AC	Aircraft
ACARS	Aircraft Communications Addressing and Reporting System
ACS	Acceptable Controller Spacing
ADS-B	Automatic Dependent Surveillance - Broadcast
ADL	FAA’s Aeronautical Data Link Product Team
AEEC	Airlines Electronic Engineering Committee
AFAST	CTAS Active Final Approach Spacing Tool
AOC	Airline Operational Control
ARR	Arrival Operation
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ATL	Atlanta Hartsfield International Airport
ATM	Air Traffic Management
BADA	Eurocontrol Base of Aircraft Data
BDL	Bradley International Airport
BNA	Nashville International Airport
BOS	Boston Logan International Airport
BWI	Baltimore-Washington International Airport
CA	Conflict Probe Correct Alert
CAS	Calibrated Airspeed
CENA	Center d’Etudes de la Navigation Aerienne
Center	Air Route Traffic Control Center (ARTCC)
cl	Climb flight mode
CLE	Cleveland Hopkins International Airport
CLT	Charlotte-Douglas International Airport
CPDLC	Controller-Pilot Data Link Communication
cr	Cruise flight mode
CTAS	Center/TRACON Automation System
CVG	Cincinnati-Northern Kentucky International Airport
d	Descent flight mode
D2	CTAS Direct-To Tool
DADI	Downlink of Aircraft Derived Information
DAG-TM	Distributed Air-Ground Traffic Management
DAP	Downlink of Aircraft Parameters
DCA	Washington National International Airport
DEN	Denver International Airport
DEP	Departure Operation
DFW	Dallas-Ft. Worth International Airport
DGAC	Direction General de l’Aviation Civile (French)
DIR	Direct Routing

DSSS	Decision Support System Services
DST	Decision Support Tool
DTW	Detroit Metro Wayne County International Airport
EDA	CTAS En Route/Descent Advisor
EDX	En Route Data Exchange
ETMS	Enhanced Traffic Management System
EWR	Newark International Airport
FA	Conflict Probe False Alert
FAA	Federal Aviation Administration
FANG	FMS-ATM Next Generation project
FFP1	FAA’s Free Flight Phase 1 Program
FLL	Ft. Lauderdale Hollywood International Airport
FMS	Flight Management System
FSF	Fuel Scale Factors
ft	feet
HCS	ARTCC Host Computer System
HOU	Houston Hobby International Airport
IAD	Washington Dulles International Airport
IAH	Houston–Intercontinental International Airport
IAT	Integrated Air Traffic Model
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
ITWS	Integrated Terminal Weather Service
JFK	N.Y. Kennedy International Airport
kt	knot, nautical mile per hour
LAS	Las Vegas McCarran International Airport
LAX	Los Angeles International Airport
LGA	N.Y. LaGuardia Airport
LNAV	Lateral Navigation
MA	Conflict Probe Missed Alert
MCO	Orlando International Airport
MDW	Chicago Midway International Airport
MEM	Memphis International Airport
MF	Metering Fix
MHS	Minimum Horizontal Separation
MIA	Miami International Airport
MSP	Minneapolis-St. Paul International Airport
NAS	National Airspace System
NASSI	NAS Status Information
NASA	National Aeronautics and Space Administration
NLR	National Aerospace Laboratory (Dutch)
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration

OAK	Oakland International Airport
OM	Outer Marker
ORD	Chicago O'Hare International Airport
OVR	Overflight Operation
PAZ	Protected Airspace Zone
PCA	Point of Closest Approach
PDX	Portland International Airport
pFAST	CTAS Passive-Final Approach Spacing Tool
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
PIT	Greater Pittsburgh International Airport
RTA	Required Time of Arrival
rss	Root-Sum-Squared
RUC	Rapid Update Cycle
SAN	San Diego International Airport
SCC	FAA Systems Command Center
SEA	Seattle-Tacoma International Airport
SFO	San Francisco International Airport
SID	Standard Instrument Departure
SLC	Salt Lake City International Airport
SRC	System Resources Corporation
STA	Scheduled Time of Arrival
STAR	Standard Terminal Arrival
STL	St. Louis Lambert International Airport
STNA	Service Technique de la Navigation Aerienne (French)
TH	Runway Threshold
TMA	CTAS Traffic Management Advisor
TRACON	Terminal Radar Approach Control
TS	Trajectory Synthesizer, a CTAS Software Process that predicts 4D aircraft trajectories
TW	ITWS Terminal Winds Program
URET CCLD	User-Request Evaluation Tool, Core Capabilities Limited Deployment
VDL	Very High Frequency Data Link
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VNAV	Vertical Navigation, a mode of the FMS that calculates a vertical trajectory profile
Wx	Weather
ZAB	Albuquerque, NM ARTCC
ZAU	Chicago, IL ARTCC
ZBW	Nashau, NH ARTCC
ZDC	Leesburg, VA ARTCC
ZDV	Denver, CO ARTCC
ZFW	Ft.Worth, TX ARTCC

ZHU	Houston, TX ARTCC
ZID	Indianapolis, IN ARTCC
ZJX	Jacksonville, FL ARTCC
ZKC	Kansas City, KS ARTCC
ZLA	Los Angeles, CA ARTCC
ZLC	Salt Lake City, UT ARTCC
ZMA	Miami, FL ARTCC
ZME	Memphis, TN ARTCC
ZMP	Minneapolis, MN ARTCC
ZNY	New York, NY ARTCC
ZOA	Oakland, CA ARTCC
ZOB	Cleveland, OH ARTCC
ZSE	Seattle, WA ARTCC
ZTL	Atlanta, GA ARTCC

Appendix A US/European Data Exchange Efforts

U.S. and European programs pursuing enhanced ATM/DST performance through user-ATM data exchange, include the following key efforts:

- FAA Enhanced Surveillance Systems Engineering Group– This group (AND-402) is focusing on the use of Mode-S (GICB protocol) as a near-term low-cost method to downlink time-critical aircraft data to enhance ATM/DST operations [51-54].

- FAA Aeronautical Data Link (ADL) Decision Support System Services (DSSS) Group – This aeronautical data link subgroup (AND-370) is focused on ATM Decision Support System services to enhance NAS performance. One basic service involves user-ATM data exchange of DST input data, focusing on two-way data exchange via CPDLC through and beyond datalink plans and programs [55].

- FAA Collaborative Decision Making (CDM) – This group is evaluating the NAS enhancements possible by integrating ATM Systems Command Center (SCC) and regional Center/TRACON facilities with AOC Airline dispatchers [56].

- NASA En Route Operations Branch – This group is building en route CTAS DSTs through the Advanced Air Transportation Technologies (AATT) program [57]. A recent Distributed Air-Ground Traffic Management (DAG-TM) initiative is focusing AATT efforts on integrated services utilizing CTAS DSTs to solve NAS inefficiencies [58]. Integral to DAG-TM and embodied in the En Route Data Exchange (EDX) program is the need to provide more accurate/dynamic data, from various sources, to improve accuracy of DST trajectory prediction functions [6]. EDX has completed 2 phases of this effort. EDX Phase 1 evaluated CTAS trajectory prediction sensitivity to airline-provided estimates of weight and speed data [23]. The planned EDX Phase 2 demonstration of UAL FMS flight data to CTAS in Denver en route airspace, planned for late summer/fall 2000, is discussed separately. NASA is also supporting MIT/Lincoln Laboratory in the development of a Terminal Winds (TW) Enhancement to the Integrated Terminal Weather System (ITWS). TW/ITWS would enhance the NOAA Rapid Update Cycle (RUC) wind forecasts, used by CTAS, with regionally downlinked aircraft wind reports [59].

- RTCA SC194 WG2 – This RTCA Working group with active participation from FAA AND-370 and NASA En Route Operations is defining FMS-ATM-AOC integrated services to enhance the NAS [59]. This group continues the effort begun in the FAA FMS-ATM Next Generation (FANG) program, which produced operations concept and required capabilities documents for several integrated services [16-17,60]. This group is defining future service requirements for implementation in future data link message sets and planning. WG2's Basic Information Exchange Calibration Data Service involves two-way data exchange among FMS-ATM-AOC participants, primarily via addressable datalink, broadcast datalink, and ground-ground data link with airline dispatchers, to enhance ATM/DST performance. Other RTCA efforts include SC189 and other SC194 working groups identifying specific datalink requirements for datalink configurations and message set in the US/European community. Additionally, SC169, focused on the airline dispatcher role, is establishing the New Age Flight Plan requirements [61], as well as investigating exchanging NAS Status Information (NASSI) including ATC constraints and AOC user preferences/scheduling/flight plan updates and common weather database. Also, SC186 is defining ADS-B applications and requirements for implementing different media for ADS-B.

- AEEC Datalink (DLK) Systems Subcommittee – The Airlines Electronic Engineering Committee (AEEC) Data Link Systems Subcommittee is setting standards for the downlinking of various aircraft data elements [62]. While the focus of the AEEC to date has been on the use of the existing Aircraft Communications Addressing and Reporting System (ACARS) communication link to transmit these data, the committee is also setting the standards for the emerging Aeronautical Telecommunications Network, using VDL Mode 2 data link.

- Eurocontrol –Eurocontrol has several relevant programs devoted to aircraft-ATM data exchange [63] These include: Downlink of Aircraft Parameters (DAP), Downlink of Aircraft Derived Information (DADI) [64] led by NLR, SENA, and STNA using Mode-S.

Two past/proposed demonstrations of aircraft-ATM data exchange include:

- Eurocontrol ESCAPE – Experimentation and Simulation of Controller Access to Aircraft Parameters and Display Evaluation. (ESCAPE), a French (DGAC) project, aims to assess the benefits of the display of downlinked aircraft parameters (DAPs) on a controller screen, initially on Paris/Orly airport approach. Real-time simulations were performed at CENA in April 1998 with 20 Orly controllers [65].

- EDX Phase 2 Field Test – A joint NASA EDX/FAA AND-370 air-ground data exchange field evaluation is scheduled for Fall 2000 in Denver En Route airspace. As previously presented in the text as in Figure S.1, a United B777 aircraft will be modified to passively downlink data once per minute using ACARS technology. Shadow-mode CTAS operations will incorporate these data to assess DST performance improvements [5].

Appendix B Trajectory Prediction Accuracy

Trajectory Prediction Accuracy is defined as the accuracy of a flight trajectory predicted at a specific future location or set time horizon. This can be specified either in terms of (a) position uncertainty at a fixed future time point; or (b) timing uncertainty as to when the aircraft crosses a future range or altitude point.

In Chapter 1, the Airport Throughput Benefits used timing uncertainty of the arrival descent trajectory culminating at the arrival metering fix. This is used, in turn, to estimate downstream runway threshold separations. In Chapter 2, the Center/TRACON delay distribution benefits analysis also employs estimated arrival metering fix delivery timing accuracy to define the amount of delay that can be shifted and absorbed in upstream ARTCC airspace. In Chapter 4, the Separation Assurance ATM Interruptions benefits analysis incorporates 12-minute trajectory prediction accuracy of all flight modes (arrival, departure, over-flight), representing ATM conflict probe accuracy. Here, the assumption is that the conflict probe is looking ahead to where the aircraft will be 12 minutes into the future. In Chapter 4, the values of trajectory prediction accuracy are used to derive other ATM perception attributes, including acceptable controller spacing, perceived miss distance and probability of conflict.

This appendix derives the various trajectory prediction accuracy estimates used in these report chapters. Reference [13] includes more detail on the trajectory accuracy parameter assumptions and modeling.

Calculation of Timing Error at the End of Climb or Descent Flight Segments

We begin by defining the quantitative expression for the timing error (□t,M) for climb and descent flight segments. That is the uncertainty in timing of the trajectory crossing a certain point at the end of a climb or descent phase of flight. The variance of the climb/descent maneuver timing error was modeled using the following equation:

$$\sigma_{t,M} = \sqrt{\sum_{\forall i} A_i^2 \sigma_i^2} \qquad \text{(B.1)}$$

Where: $\sigma_{t,M}$ = Total time delay error uncertainty (e.g., metering fix crossing time error)
A_i = Sensitivity of timing error to the error in parameter *i* (e.g., surveillance error)
σ_i = Set of 10 parameters defining the progress, or characteristics, of a trajectory that are subject to error

Baseline estimates of the 10 A_i coefficients for the corresponding 10 contributing error parameters are summarized in Table B.1 for the climb and descent flight segments. Descent coefficients were based on high-fidelity aircraft simulation results, while climb coefficients reflect individual parameter sensitivities using a CTAS stand-alone system with field data. For several parameters, climb sensitivities were unknown or unmeasurable from the field data taken. In these cases (as noted in the table), the descent coefficient values were also used for climbs, as a first-cut approximation.

Table B.1 Climb and Descent Model Sensitivity Coefficients

Flight Phase Timing Error Sensitivity Coefficients			
Parameter	Units	Climb	Descent
Initial Weight	sec/%	24.2	0.88
(Thrust – Drag)	sec/%	4.08*	1.39
TOD Placement	sec/nm	N/A	4.08
Speed. Adherence	sec/kt	11.1*	1.46
X-Track Wander	sec/nm	1.77**	1.77
Aircraft Navigation Bias	sec/deg	1.94**	1.94
Turn Dynamics	sec/sec	1.11**	1.11
Wind Forecast	sec/kt	3.7*	0.95
Temperature Forecast	sec/°C	8.7*	4.62
Surveillance	sec/kt	0.26**	0.26

* Path distance errors at TOC converted to time error based on speed of 415 kts at TOC
** Climb coefficients set equal to descent coefficients, due to lack of climb data.

Table B.2 presents the contributing error parameter values required to calculate ATM trajectory prediction timing accuracy using Equations (B.1). The error statistics in Table B.2 are presented in the form of a root-sum-square (rss) error. Reference [13] provides supporting detail on the component mean and standard deviation (σ) of the error used to derive the rss for each parameter and ATM DST technology case. Here, values are presented for the Active Baseline and the EDX cases. These values draw extensively from the literature, current research, and supplemented by discussions with NASA conflict probe experts to quantitatively differentiate the various proposed technology cases by flight mode. In all cases, these error parameter values assume jet aircraft with an onboard FMS flight control (LNAV and VNAV) in the en route airspace.

A key limitation in predicting climb and descent timing before EDA is the lack of common ATM-aircraft knowledge of speed profile and top of climb/descent location. This led to large errors in speed adherence and estimated TOD placement. These errors are reduced for metered descents under the Active Baseline with the EDA-calculated maneuver advisories, where the pilot is expected to be targeting the controller-cleared EDA descent advisory. Further EDX improvements are reflected in the shaded cells of Table B.2.

Table B.2 Trajectory Prediction Contributing Error Values (Jet with FMS)

		Active Baseline			**EDX1** (Wx)			**EDX2** (Wt,Thr/Dg)			**EDX3** (Spd Intent)		
Parameter	Units	Cl	Cr	D	Cl	Cr	D	Cl	Cr	D	Cl	Cr	D
Initial Weight	%	9.2	N/A	7.8	9.2	N/A	7.8	7.6	N/A	5.6	7.6	N/A	5.6
(Thrust – Drag)	%	5.9	N/A	5.9	5.9	N/A	5.9	2.1	N/A	2.1	2.1	N/A	2.1
TOD Placement	nm	N/A	N/A	0.25	N/A	N/A	0.25	N/A	N/A	0.25	N/A	N/A	0.25
Speed Adherence (1) ($\sigma_{V,FTE}$)	kt	15	15	4.0	15	15	4.0	15	15	4.0	4.0	15	4.0
X-Track Wander	nm	0.14	N/A	0.14	0.14	N/A	0.14	0.14	N/A	0.14	0.14	N/A	0.14
AC Navigation Bias	deg.	0.15	N/A	0.15	0.15	N/A	0.15	0.15	N/A	0.15	0.15	N/A	0.15
Turn Dynamics	Sec	2.3	N/A	2.3	2.3	N/A	2.3	2.3	N/A	2.3	2.3	N/A	2.3
Wind Forecast ($\sigma_{V,w}$)	kt	12.0	13.4	12.0	8.9	10.5	8.9	8.9	10.5	8.9	8.9	10.5	8.9
Temperature Forecast	°C	1.0	N/A	1.0	0.5	N/A	0.5	0.5	N/A	0.5	0.5	N/A	0.5
Surveillance-Speed ($\sigma_{V,S}$)	kt	13.1	12.5	13.1	13.1	12.5	13.1	13.1	12.5	13.1	13.1	12.5	13.1
Surveillance-Position	nm	N/A	0.87	N/A	N/A	0.87	N/A	N/A	0.87	N/A	N/A	0.87	N/A

(1) Includes components of mismatched CTAS-FMS speed targets and aircraft flight technical error.

Key Error Sources/References:
Initial Weight – Baseline rss and EDX2 sigma error of airline fleet data [8].
Thrust & Drag – Baseline rss and EDX2 sigma error only of NASA TSRV test results[34].
TOD Placement – Baseline CTAS-FMS mismatch, EDA FMS typical RNAV error rss of 0.25 nm.
Speed Adherence – Baseline CTAS-FMS mismatch & FTE, EDA improves arrival target and EDX3 improves climb/descent target to strictly reflect FMS flight technical error [34].
X-Track Wander – Baseline rss [35].
AC Navigation Error – Baseline FMS GPS/INS Guidance system error of 0.14 degrees.
Turn Dynamics – Baseline FMS-guided rss error [36].
Wind Forecast – Baseline RUC 3-hour forecast, EDX1 improves to ITWS/TW rss error [37].
Temperature Forecast – Baseline RUC 3-hour forecast, EDX1 improve assumed to be nowcast rss error [38].
Radar Surveillance – Baseline along-track position and ground speed error of SSR [34].

Calculation of Position Error at the End of Climb, Cruise or Descent Flight Segments

We next define a quantitative expression for trajectory position prediction accuracy at the ends of climb, cruise and descent phases of flight. Here it is assumed that the climb phase ends with a cruise segment, the descent phase begins with a cruise segment, and the cruise phase is at a constant altitude. In each case, a fixed time horizon is used to define the end point of the particular phase.

A convenient mathematical model for determining the along-track position error of a single aircraft at a certain time point into the future can be described by the following equation:

$$\sigma_{P,\mathrm{Pred}}(\tau) = \sqrt{\sigma_P^2 + \tau^2 \sigma_V^2} \qquad \text{(B.2)}$$

Where: $\sigma_{P,Pred}$ = Predicted trajectory position error
$\sigma_P,\ \sigma_V$ = Position and velocity error terms
τ = Time period of flight cruise segment subject to velocity errors

The first variance term in Equation (B.2) represents either the initial or intermediate position error contribution of the trajectory. For a climb trajectory consisting of a climb segment followed by a cruise segment, it represents the position error at the end (top) of the climb segment. For a descent trajectory consisting of cruise and descent segments, it represents the contribution to position error due to the descent segment alone (i.e., at the end of the descent segment.) Thus, this position error term is directly related to the climb or descent timing error described previously by Equation (B.1) for those trajectories that have climb or descent segments. That is, if we use some average trajectory ground speed V_M, then:

$$\sigma_P = \sqrt{\sigma_{t,M}^2 V_M^2} \qquad \text{(B.3)}$$

Where: V_M = Average velocity during the climb or descent segment

In this study, an average climb or descent ground speed of 350 kts was used. This is the rough average of arrival/departure meter fix crossing speed of 280 kts and TOD/TOC speed of 415 kts.

For a cruise trajectory, the first term in Equation (B.2) represents the uncertainty in position of the aircraft at the beginning of that trajectory. This is simply the error in the surveillance system position measurement at that time.

In Equation (B.2), σ_V represents the velocity-related error contribution that accrues during the cruise segment of the trajectory with a particular time horizon. This term is expanded as:

$$\sigma_v = \sqrt{\sigma_{V,S}^2 + \sigma_{V,W}^2 + \sigma_{V,FTE}^2} \qquad \text{(B.4)}$$

Where: $\sigma_{V,S}$, $\sigma_{V,W}$, $\sigma_{V,FTE}$ = Surveillance, wind, and speed adherence error terms from Table B.2.

Time Horizon and τ for Climb, Cruise, and Descent Trajectories

In Equation (B.2), for the climb trajectory, the parameter τ is set to the portion of the trajectory that is assumed to remain after the climb segment is complete. For the descent trajectory, τ is set to the time period of the cruise segment that precedes the descent segment. For the cruise trajectory, τ is set to the entire length of the trajectory time horizon being investigated.

In this study, advisories from the DSTs are assumed to be provided to controllers at 20 minutes before some predicted future conflict event. This is assumed to be followed by an 8-minute controller/pilot lag, resulting in a 12-minute time horizon. This 8-minute lag covers both the controller issuance and pilot initiation of the resolution maneuver. Although a DST technology-specific time horizon would likely be chosen to trade-off high false/missed alerts with the cost of conflict resolution, this simplifying 12-minute common time horizon was chosen to represent all cases.

For conflicts predicted to occur during cruise flight, only cruise trajectory prediction errors contribute. In this case, the value of τ in Equation (B.2) is set at 12 minutes. For conflicts identified to occur during either climb or descent flight, the conflict probe time horizon is assumed to nominally encompass half the climb or descent segment error, with the remaining time period accruing cruise accuracy errors. A 20-minute climb (10,000 ft to the TOC) and 15-minute descent (TOD to 10,000 ft) were assumed. Thus, for a climb trajectory, it is assumed that 10 minutes of the trajectory is from the climb segment, and τ is set at 2 minutes to cover the remaining cruise segment. For a descent trajectory, it is assumed that 7.5 minutes of the trajectory is from the descent segment, and τ is set to 4.5 minutes to cover the preceding cruise segment.

This approximate trajectory model is illustrated in Figure B.1 for arrivals. In Figure B.1, the prediction accuracy of a conflict predicted to involve a descending aircraft (at conflict PCA), but predicted while that aircraft was in cruise would include error contributions from both descent (half of 15-minute descent duration) and cruise (remaining 4.5 minutes) flight segments. Conversely, the prediction accuracy of a conflict predicted to involve a cruising arrival flight (PCA occurs prior to descent) would include only cruise error contributions. Parallel situations apply to trajectory accuracy of departure climb and cruise flight segments.

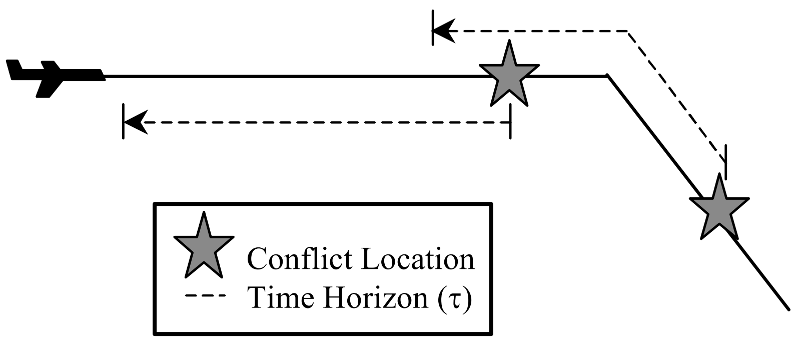


Figure B.1 Arrival Conflict Time Horizon

Estimated Trajectory Prediction Accuracy

Trajectory prediction accuracies in both timing and position are estimated using Table B.2 error parameter values in Equations (B.1) through (B.4), along with Table B.1 climb/descent timing sensitivity coefficients and the common 12-minute time horizon value. Table B.3 shows the error contributions and resulting 12-minute trajectory prediction error in climb, cruise and descent segments for arrival, overflight, and departure operations. The first row presents the timing error from Equation B.1 for the Active Baseline and EDX cases. The second and third rows represent the position and velocity terms for Equation (B.2). For the climb and descent segments, the position error term is derived from the corresponding timing error term using Equation (B.3). The last row of Table B.3 shows composite predicted position error resulting from these calculations for the various flight phases. In the case of arrival-descent and departure-climb conflicts, the 12-minute trajectory prediction error includes a combination of climb or descent segment and cruise segment errors. Note that the Active Baseline descent maneuver timing error was calibrated to approximate the 15-20 second arrival fix delivery accuracy observed in the 1992-1995 EDA prototype field tests [20]. Note also that shading of a cell in Table B.3 indicates improvement from the previous case.

Table B.3 Assumed ATM Trajectory Prediction Accuracy

	Units	Active Baseline					EDX1 (Weather)				
		DEP		OVR	ARR*		DEP		OVR	ARR*	
		CL	CR	CR	CR	D	CL	CR	CR	CR	D
Error Components											
Maneuver $\sigma_{t,M}$	sec	283	NA	NA	NA	**17.9**	281	NA	NA	NA	15.6
Position σ_P	nm	13.7	0.87	0.87	0.87	0.87	13.7	0.87	0.87	0.87	0.76
Velocity σ_V	nm/min	0.39	0.39	0.39	0.30	0.30	0.36	0.39	0.38	0.29	0.27
12-minute Trajectory Prediction Accuracy											
Predicted Position Error $\sigma_{p,pred}(\tau)$	nm	13.8	4.7	4.7	3.7	1.6	13.7	4.7	4.6	3.6	1.4

	Units	EDX2 (Aircraft Weight)					EDX3 (Speed Intent)				
		DEP		OVR	ARR*		DEP		OVR	ARR	
		CL	CR	CR	CR	D	CL	CR	CR	CR	D
Error Components											
Maneuver $\sigma_{t,M}$	sec	251	NA	NA	NA	12.8	192	NA	NA	NA	12.8
Position σ_P	nm	12.2	0.87	0.87	0.87	0.62	9.4	0.87	0.87	0.87	0.62
Velocity σ_V	nm/min	0.36	0.39	0.38	0.29	0.27	0.27	0.29	0.29	0.30	0.27
12-minute Trajectory Prediction Accuracy											
Predicted Position Error $\sigma_{p,pred}(\tau)$	nm	12.2	4.7	4.6	3.6	1.4	9.4	3.6	3.6	3.6	1.4

Note: Bold value calibrated to approximate 15-20 second (1-sigma) metering fix delivery error of EDA [20] prototype field tests.
* Applies to metered arrivals only.

Again, both Chapters 1 and 2 employ the arrival descent maneuver timing error (i.e., arrival metering fix delivery error) in the benefits calculations. Chapter 4 employs the 12-minute trajectory prediction accuracy of all flight phases, as part of ATM perception assumed in the estimation of separation assurance benefits.

Appendix C Airport Throughput Analysis Details

Table C.1 Combined Threshold Excess Spacing Buffer (sec)

	Passive Baseline				**Active Baseline**		
	Trailing Aircraft				Trailing Aircraft		
Lead a/c:	Small	Large	Heavy		Small	Large	Heavy
Small	0.86	0.89	0.95		0.74	0.75	0.80
Large	0.91	0.88	0.94		0.78	0.75	0.80
Heavy	0.96	0.95	0.96		0.84	0.82	0.81
	EDX1				**EDX1**		
	Trailing Aircraft				Trailing Aircraft		
Lead a/c:	Small	Large	Heavy		Small	Large	Heavy
Small	0.86	0.89	0.95		0.74	0.75	0.80
Large	0.91	0.88	0.94		0.78	0.75	0.80
Heavy	0.96	0.95	0.96		0.84	0.82	0.81
	EDX2				**EDX2**		
	Trailing Aircraft				Trailing Aircraft		
Lead a/c:	Small	Large	Heavy		Small	Large	Heavy
Small	0.86	0.89	0.95		0.74	0.75	0.80
Large	0.91	0.88	0.94		0.78	0.75	0.80
Heavy	0.96	0.95	0.96		0.84	0.82	0.81
	EDX3				**EDX3**		
	Trailing Aircraft				Trailing Aircraft		
Lead a/c:	Small	Large	Heavy		Small	Large	Heavy
Small	0.86	0.88	0.95		0.74	0.75	0.80
Large	0.91	0.88	0.94		0.78	0.75	0.80
Heavy	0.96	0.95	0.96		0.84	0.82	0.81
	EDX4				**EDX4**		
	Trailing Aircraft				Trailing Aircraft		
Lead a/c:	Small	Large	Heavy		Small	Large	Heavy
Small	0.83	0.86	0.92		0.71	0.73	0.77
Large	0.85	0.86	0.91		0.72	0.73	0.77
Heavy	0.86	0.88	0.92		0.74	0.75	0.78

Table C.2 Assumed Airport Runway Configurations

	Configuration	Arrival Runways	Departure Runways
Atlanta (ATL)	IFR & VFR	08L, 09R	08R, 09L
Nashville (BNA)	IFR & VFR	02C, 02R	02L, 02R, 31
Boston (BOS)	IFR	04R	04R, 04L, 09
	VFR	04R, 04L	04R, 04L, 09
Baltimore (BWI)	IFR	15R, 15L, 10	15R, 15L
	VFR	33L, 33R, 28 22	33R, 28, 22
Charlotte (CLT)	IFR & VFR	36L, 36R	36L, 36R
Cincinnati (CVG)	IFR & VFR	18L, 18R	18L, 18R, 27
Washington National (DCA)	IFR	36	36, 33, 03
	VFR	36, 33, 03	36, 33, 03
Denver (DEN)	IFR & VFR	34, 35L, 35R	34, 35L, 35R
Dallas-Ft. Worth (DFW)*	IFR	36L, 35C, **35R**	35L, 36R
	VFR	36L, 35C, **35R**, 31R	35L, 36R, 31L
Detroit (DTW)	IFR & VFR	03L, 03R	03C, 03L
N.Y. Newark (EWR)	IFR	04R	04L
	VFR	04R, 11	04L, 11
Washington Dulles (IAD)	IFR	01R	01L, 30
	VFR	01R, 01L	01L, 30
Houston Intercontinental (IAH)	IFR	26, 27	14L, 14R
	VFR	08, 09	14L, 14R
N.Y. Kennedy (JFK)	IFR & VFR	13L, 13R	13L, 13R
Las Vegas (LAS)	IFR	25R, 25L	25R, 25L
	VFR	19L, 25R, 25L	19L, 25R, 25L
Los Angeles (LAX)	IFR	25L, 24R	25R, 24L
	VFR	25L, 24R	25R, 24L
N.Y. LaGuardia (LGA)	IFR	04	13
	VFR	22	13
Orlando (MCO)	IFR	18L, 17	18R, 17
	VFR	18R, 18L, 17	18R, 18L, 17
Memphis (MEM)	IFR	**18L**, 18R	18C, 18R
	VFR	**18L**, 18R, 27	18C, 18R
Miami (MIA)	IFR	09L, 09R	09L, 09R, 12
	VFR	09L, 09R, 12	09L, 09R, 12
Minneapolis (MSP)	IFR & VFR	29L, 29R	29L, 29R
Chicago O'Hare (ORD)	IFR	14R, 14L	09R, 09L
	VFR	14R, 22R, 22L	27L, 22R
Philadelphia (PHL)	IFR & VFR	27R, 17	27L, 17
Phoenix (PHX)	IFR	08R	08L
	VFR	08L, 08R	08L, 08R
Pittsburgh (PIT)	IFR & VFR	10L, 10R	10C, 14
Seattle (SEA)	IFR	16R	16L
	VFR	16L, 16R	16L, 16R
San Francisco (SFO)	IFR	28R	28L, 28R
	VFR	28R, 28L	01L, 01R
Salt Lake City (SLC)*	IFR	**34L**, 34R	34R, 35
	VFR	**34L**, 34R	**34L**, 34R, 35
St. Louis (STL)	IFR	30L, 30R	30L, 30R
	VFR	30L, 30R, 24	30L, 30R

* New airport runways indicated in **bold** type

Table C.3 Airport Characteristics

Airport		Historical Share (%)	1996 Airport Cost Rates ($/min) **	
		IMC*	Departure	Arrival
ATL	Atlanta	14.2%	27.76	35.60
BDL	Bradley	14.6%	16.92	21.72
BNA	Nashville	9.5%	14.54	18.44
BOS	Boston	15.6%	19.74	25.11
BWI	Baltimore	12.4%	19.37	24.65
CLE	Cleveland	15.6%	21.54	27.44
CLT	Charlotte	12.5%	18.50	23.48
CVG	Cincinnati	15.0%	19.52	24.99
DCA	Washington National	10.7%	20.99	26.62
DEN	Denver	6.0%	23.71	30.25
DFW	Dallas/Ft. Worth	8.4%	23.53	30.08
DTW	Detroit	16.6%	24.54	31.27
EWR	Newark	16.6%	24.99	32.09
FLL	Ft. Lauderdale	3.0%	18.14	23.17
HOU	Houston Hobby	13.5%	18.64	23.94
IAD	Washington Dulles	11.7%	16.90	21.53
IAH	Houston Intercontinental	12.7%	22.15	28.34
JFK	N.Y. Kennedy	15.0%	34.19	44.75
LAS	Las Vegas	0.3%	20.33	25.83
LAX	Los Angeles Int'l	22.2%	26.45	33.96
LGA	N.Y. LaGuardia	16.4%	23.30	29.72
MCO	Orlando	5.9%	21.19	27.05
MDW	Chicago Midway	15.1%	20.31	26.02
MEM	Memphis	9.2%	23.52	30.23
MIA	Miami	2.3%	23.60	30.32
MSP	Minneapolis	11.6%	22.23	28.30
OAK	Oakland	14.4%	14.14	18.18
ORD	Chicago O'Hare	16.1%	26.91	34.53
PDX	Portland	10.2%	18.40	23.50
PHL	Philadelphia	15.0%	20.37	25.91
PHX	Phoenix	0.5%	20.84	26.44
PIT	Pittsburgh	24.6%	19.14	24.23
SAN	San Diego	12.6%	25.76	32.96
SEA	Seattle	14.9%	23.33	29.84
SFO	San Francisco	12.5%	27.46	35.26
SLC	Salt Lake City	5.6%	20.96	26.84
STL	St. Louis	11.5%	22.33	28.46

(1) Annual Occurrence of IMC (percent) 7AM-10PM [66]

* Average value, weighted by aircraft class distribution. Departure rates assume ground hold rates, arrival rates assume airborne rates.

Table C.4 Airport Operations, Delays, and Rush Arrival Rates

Airport	CY1996 Airport Operations	CY1996 Delays >15 min per 1000 ops (1)	Delay Category No.	Rush Arrival Rate per 100 ops (2) Arr	Dep
EWR - Newark	443,431	65.25	1	39.46	47.45
SFO - San Francisco	442,281	56.57	1	39.46	47.45
LGA - N.Y. LaGuardia	342,618	46.22	1	39.46	47.45
ORD - Chicago O'Hare	909,186	34.46	2	34.91	41.97
STL - St. Louis	517,352	34.04	2	34.91	41.97
JFK - N.Y. Kennedy	360,511	29.53	2	34.91	41.97
BOS - Boston	462,507	26.37	2	34.91	41.97
LAX - Los Angeles	764,002	24.13	3	30.35	36.50
ATL - Atlanta	772,597	23.88	3	30.35	36.50
DFW - Dallas-Ft. Worth	869,831	19.59	3	30.35	36.50
PHL - Philadelphia	406,121	17.95	3	30.35	36.50
IAH - Houston International	391,939	11.45	4	24.28	29.20
CVG - Cincinnati	393,523	10.38	4	24.28	29.20
MSP - Minneapolis	483,570	9.29	4	24.28	29.20
DTW - Detroit	531,098	9.10	4	24.28	29.20
PHX - Phoenix	544,363	7.25	4	24.28	29.20
IAD - Washington Dulles	330,439	6.81	4	24.28	29.20
MIA - Miami	546,487	6.79	4	24.28	29.20
MDW - Chicago Midway	254,351	6.70	4	24.28	29.20
PIT - Pittsburgh	447,436	6.60	4	24.28	29.20
CLT - Charlotte	457,054	6.55	4	24.28	29.20
DCA - Washington National	309,754	6.53	4	24.28	29.20
SEA - Seattle	397,591	6.37	4	24.28	29.20
CLE - Cleveland	291,029	4.68	5	18.21	21.90
MCO - Orlando	341,942	4.59	5	18.21	21.90
LAS - Las Vegas	479,625	3.68	5	18.21	21.90
BWI - Baltimore-Washington	270,156	3.67	5	18.21	21.90
SLC - Salt Lake City	373,815	3.53	5	18.21	21.90
SAN - San Diego	243,595	3.31	5	18.21	21.90
HOU - Houston Hobby	252,254	2.57	5	18.21	21.90
PDX - Portland	305,964	2.41	5	18.21	21.90
DEN - Denver	454,234	1.90	5	18.21	21.90
FLL - Ft. Lauderdale	236,342	1.53	5	18.21	21.90
BDL - Bradley	160,752	1.36	5	18.21	21.90
BNA - Nashville	226,274	0.73	5	18.21	21.90
MEM - Memphis	363,945	Not Available	5	18.21	21.90
OAK - Oakland	516,498	Not Available	5	18.21	21.90

(1) Source: FAA "1997 Aviation Capacity Enhancement Plan," Office of System Capacity. (Dec 1997)

(2) Rush Arrival rates assumed to be 130%,115%, 100%, 80% and 60% of simulated DFW rush arrival rate [12], based on 1996 FAA delay data and category criteria shown in Table C.5

Table C.5 Rush Arrival Rate Criteria

Category No.	CY1996 (1) Delays > 15 minutes Per 1000 Airport Ops	Proportion of DFW (category 3) Rush Arrival Rate	Rush Arrival Rate (Rush Arrivals Per 100 Airport Ops)
1	>35	130%	39.46
2	25-35	115%	34.91
3	15-25	100%	30.35 (2)
4	5-15	80%	24.28
5	<5	60%	18.21

(1) FAA CY1996 Delay Data [25], as shown in Table C.4.
(2) DFW Rush Arrival Rate per Separation Assurance ATM Interruptions analysis of Chapters 4.

Table C.6 FAA-Based 1998 Time and Fuel Cost Rates by Aircraft Class

Engine Type	Engine Num	A/C Size	A/C Class	FAA-Based Cost Rates ($/hr) Time Cost Crew	Maint.	Subtotal	Fuel & Oil Cost Airborne	Ground**	Fuelburn* (lbs/min) Gd Hold (1)
J	4	H	4JH	2,488	1,699	4,187	2,703	901	150
J	4	L	4JL	582	990	1,572	829	276	46
J	3	H	3JH	1,981	1,459	3,440	1,827	609	102
J	3	L	3JL	1,188	712	1,900	1,025	342	57
J	3	S+	3JS+	280	596	876	626	209	35
J	2	H	2JH	1,489	780	2,269	1,152	384	64
J	2	LH	2JLH	1,164	493	1,657	754	251	42
J	2	L	2JL	851	531	1,382	651	217	36
J	0	L	JL	701	527	1,228	593	198	33
J	2	LS	2JLS	551	523	1,074	535	178	30
J	2	S+	2JS+	251	515	766	420	140	23
J	0	S+	JS+	238	438	676	335	112	19
J	2	S	2JS	225	361	586	249	83	14
J	1	L	1JL	240	400	640	300	110	18
J	1	S+	1JS+	175	250	425	210	80	13
J	1	S	1JS	110	180	290	130	50	8
T	4	L	4TL	672	998	1,670	571	190	32
T	3	L	3TL	439	671	1,110	421	140	23
T	2	L	2TL	205	344	549	270	90	15
T	0	L	TL	203	324	527	226	75	13
T	2	S+	2TS+	201	303	504	181	60	10
T	0	S+	TS+	197	280	477	164	55	9
T	2	S	2TS	193	257	450	147	49	8
T	0	S	TS	155	199	354	128	43	7
T	1	S+	1TS+	117	140	257	109	36	6
T	1	S	1TS	114	110	224	103	34	6
P	4	L	4PL	250	275	525	500	167	28
P	3	S	3PS	220	245	465	445	148	25
P	2	L	2PL	190	215	405	390	130	22
P	2	S+	2PS+	200	204	404	193	64	11
P	0	S+	PS+	136	149	285	131	44	7
P	2	S	2PS	72	93	165	68	23	4
P	0	S	PS	72	77	149	57	19	3
P	1	S+	1PS+	72	60	132	45	15	3
P	1	S	1PS	72	27	99	22	7	1
(Rockwell I	0	0	SST	2,488	1,699	4,187	7,363	2,454	409
J	8	L	8JH	2,488	1,699	4,187	2,703	901	150

Consumer Price index (CPI)		Oil & Gas Deflater	
1982-84 base	100.0	1992 base	100
1996	153.0	1996	104.2

Escalation Factor		Crew	Maint	Subtotal	Airbourne	Ground
1996	1.000	1.000	1.000	1.000	1.000	1.000

Note: Shaded aircraft classes are interpolated/extrapolated from non-shaded values of FAA source.

* Assumes Fuelcost of $0.10/lb

** Ground Fuel and oil cost is assumed to be 1/3 of airbourne per advice of airline personnel.

Sources: FAA, "Economic Values for Evaluation of Federal Administration Investment and Regulatory Programs," Final Report FAA-APO-98-8, Office of Aviation Policy and Plans. (June 1998)

FAA, "FAA Aviation Forecasts Fiscal Years 1998-2009," Final Report FAA-APO-98-1, Office of Avaiation Policy and Plans. (March 1998)

Table C.7 CY1996 Domestic ARTCC Operations

	ARTCC Facility	ARTCC Departure Ops	ARTCC Overflight Ops	ARTCC Total Ops (1)
ZAB	Albuquerque, NM ARTCC	506,188	493,112	1,505,488
ZAU	Chicago, IL ARTCC	1,180,494	533,343	2,894,331
ZBW	Nashau, NH ARTCC (BOS)	697,875	331,101	1,726,851
ZDC	Leesburg, VA ARTCC (DC)	831,358	668,368	2,331,084
ZDV	Denver, CO ARTCC	434,387	658,530	1,527,304
ZFW	Ft.Worth, TX ARTCC	854,283	409,328	2,117,894
ZHU	Houston, TX ARTCC	825,674	201,509	1,852,857
ZID	Indianapolis, IN ARTCC	669,509	882,649	2,221,667
ZJX	Jacksonville, FL ARTCC	607,723	662,712	1,878,158
ZKC	Kansas City, KS ARTCC	691,746	602,863	1,986,355
ZLA	Los Angeles, CA ARTCC	927,509	125,726	1,980,744
ZLC	Salt Lake City, UT ARTCC	378,163	752,723	1,509,049
ZMA	Miami, FL ARTCC	725,485	90,866	1,541,836
ZME	Memphis, TN ARTCC	575,462	827,193	1,978,117
ZMP	Minneapolis, MN ARTCC	762,151	503,146	2,027,448
ZNY	New York, NY ARTCC	763,938	511,985	2,039,861
ZOA	Oakland, CA ARTCC	616,385	135,186	1,367,956
ZOB	Cleveland, OH ARTCC	967,543	935,158	2,870,244
ZSE	Seattle, WA ARTCC	647,722	97,069	1,392,513
ZTL	Atlanta, GA ARTCC	943,365	565,941	2,452,671
ZAN	Anchorage, A ARTCC	225,034	45,121	495,189
ZUA	Guam CERAP	32,112	8,560	72,784

(1) ARTCC Total Operations is calculated as: 2 x (ARTCC Departure ops) + (ARTCC Overflight Ops)

Source: Office of Aviation Policy and Plans, Washington, DC 20591, Air Traffic Activity query, APO Data System, FAA APO Home Page, Internet WWW Site (Nov 19,1998).

Appendix D Center/TRACON Delay Distribution Calculations

Table D.1a ATL Center/TRACON Delay Distribution Fuel Savings, Passive Baseline

			Passive Baseline									
	Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec) BL	EDX1	EDX2	EDX3	EDX4		Fuel burn Savings ($) EDX1	EDX2	EDX3	EDX4
Rush	Straight-In	28	138	137	137	132	125	Per Arr	$0.09	$0.09	$0.54	$1.18
1	Downwind	14						Per Arr	$0.09	$0.09	$0.54	$1.18
								Per Rush	$4	$4	$22	$47
Rush	Straight-In	35	160	159	159	154	147	Per Arr	-	-	$0.54	$1.18
2	Downwind	27						Per Arr	$0.09	$0.09	$0.54	$1.18
								Per Rush	$2	$2	$34	$73
Rush	Straight-In	33	162	161	160	155	148	Per Arr	-	-	$0.54	$1.18
3	Downwind	31						Per Arr	$0.09	$0.18	$0.54	$1.18
								Per Rush	$3	$6	$41	$81
Rush	Straight-In	36	171	170	170	164	157	Per Arr	-	-	$0.64	$1.27
4	Downwind	43						Per Arr	$0.09	$0.09	$0.64	$1.27
								Per Rush	$4	$4	$50	$100
Rush	Straight-In	48	170	169	168	163	156	Per Arr	-	-	$0.64	$1.27
5	Downwind	29						Per Arr	$0.09	$0.18	$0.64	$1.27
								Per Rush	$3	$5	$49	$98
Rush	Straight-In	59	187	186	185	180	173	Per Arr	-	-	$0.64	$1.27
6	Downwind	57						Per Arr	$0.09	$0.18	$0.64	$1.27
								Per Rush	$5	$10	$74	$147
Rush	Straight-In	52	181	180	179	173	166	Per Arr	-	-	$0.73	$1.36
7	Downwind	47						Per Arr	$0.09	$0.18	$0.73	$1.36
								Per Rush	$4	$8	$72	$135
Rush	Straight-In	54	185	184	183	177	170	Per Arr	-	-	$0.73	$1.36
8	Downwind	55						Per Arr	$0.09	$0.18	$0.73	$1.36
								Per Rush	$5	$10	$79	$148
Rush	Straight-In	30	161	160	159	154	147	Per Arr	-	-	$0.64	$1.27
9	Downwind	33						Per Arr	$0.09	$0.18	$0.64	$1.27
								Per Rush	$3	$6	$40	$80

Table D.1b ATL Center/TRACON Delay Distribution Fuel Savings, Active Baseline

			Active Baseline							
	Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec) BL	EDX1	EDX2/2	EDX4		Fuel burn Savings ($) EDX1	EDX2/3	EDX4
Rush 1	All	40	29	25	21	14	Per Arr	$0.36	$0.73	$1.36
							Per Rush	$15	$29	$54
Rush 2	All	62	33	29	24	17	Per Arr	$0.36	$0.82	$1.45
							Per Rush	$23	$51	$90
Rush 3	All	64	34	29	24	17	Per Arr	$0.45	$0.91	$1.54
							Per Rush	$29	$58	$99
Rush 4	All	79	36	31	25	18	Per Arr	$0.45	$1.00	$1.63
							Per Rush	$36	$79	$129
Rush 5	All	77	35	31	25	18	Per Arr	$0.36	$0.91	$1.54
							Per Rush	$28	$70	$119
Rush 6	All	116	39	34	28	21	Per Arr	$0.45	$1.00	$1.63
							Per Rush	$53	$116	$190
Rush 7	All	99	38	33	27	20	Per Arr	$0.45	$1.00	$1.63
							Per Rush	$45	$99	$162
Rush 8	All	109	38	34	27	20	Per Arr	$0.36	$1.00	$1.63
							Per Rush	$40	$109	$178

Rush 9	All	63	33	29	24	17	Per Arr Per Rush	$0.36 $23	$0.82 $51	$1.45 $91

Table D.2a LAX Center/TRACON Delay Distribution Fuel burn Savings, Passive Baseline

	Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec) BL	EDX1	EDX2	EDX3	EDX4	Passive Baseline	Fuel burn Savings ($) EDX1	EDX2	EDX3	EDX4
Rush	Straight-In	12						Per Arr	-	-	$0.40	$0.95
1	Downwind	14	123	123	122	118	111	Per Arr	-	$0.08	$0.40	$0.95
	Holding Fix	6						Per Arr	-	$0.08	$0.40	$0.95
								Per Rush	$0	$2	$12	$29
Rush	Straight-In	54						Per Arr	-	-	$0.63	$1.19
2	Downwind	52	189	188	187	181	174	Per Arr	$0.08	$0.16	$0.63	$1.19
	Holding Fix	17						Per Arr	$0.08	$0.16	$0.63	$1.19
								Per Rush	$5	$11	$77	$145
Rush	Straight-In	33						Per Arr	-	-	$0.55	$1.11
3	Downwind	30	172	171	170	165	158	Per Arr	$0.08	$0.16	$0.55	$1.11
	Holding Fix	17						Per Arr	$0.08	$0.16	$0.55	$1.11
								Per Rush	$4	$7	$44	$50
Rush	Straight-In	40						Per Arr	-	-	$0.55	$1.11
4	Downwind	33	173	172	172	166	159	Per Arr	$0.08	$0.08	$0.55	$1.11
	Holding Fix	9						Per Arr	$0.08	$0.08	$0.55	$1.11
								Per Rush	$3	$3	$46	$92
Rush	Straight-In	104						Per Arr	-	-	$0.71	$1.27
5	Downwind	71	211	209	208	202	195	Per Arr	$0.16	$0.24	$0.71	$1.27
	Holding Fix	41						Per Arr	$0.16	$0.24	$0.71	$1.27
								Per Rush	$18	$27	$154	$274

Note: Prop Holding Fixes are DARTS and SLI

Table D.2b LAX Center/TRACON Delay Distribution Fuel burn Savings, Active Baseline

	Approach Procedure	Rush Ops	Optimal TRACON Delay Setting (sec) BL	EDX1	EDX2/3	EDX4	Active Baseline	Fuel burn Savings ($) EDX1	EDX2/3	EDX4
Rush	All	31	26	22	18	11	Per Arr	$0.32	$0.63	$1.19
1							Per Rush	$10	$20	$37
Rush	All	122	39	34	28	21	Per Arr	$0.40	$0.87	$1.43
2							Per Rush	$48	$106	$174
Rush	All	80	36	31	26	19	Per Arr	$0.40	$0.79	$1.35
3							Per Rush	$32	$63	$108
Rush	All	83	36	31	26	19	Per Arr	$0.40	$0.79	$1.35
4							Per Rush	$33	$66	$112
Rush	All	216	44	38	31	24	Per Arr	$0.48	$1.03	$1.59
5							Per Rush	$103	$223	$342

Note: Prop Holding Fixes are DARTS and SLI

Appendix E Fuelburn Assumptions

Table E.1 B737 Fuelburn Rates from High-Fidelity Model Simulations [50]

	B737 Fuelburn (lbs/min)																
Cruise	CAS Cruise Speed (kts)																
Altitude (ft)	100	200	205	210	215	220	225	230	235	240	245	250	255	260	265	270	275
1000	81.6	81.6	82.6	83.6	84.9	86.2	87.7	89.3	90.9	92.8	94.8	96.9	99.0	101.4	103.9	106.4	109.0
11000	81.6	81.6	82.6	83.6	84.9	86.2	87.7	89.3	90.9	92.8	94.8	96.9	99.0	101.4	103.9	106.4	109.0
13000	80.7	80.7	81.6	82.7	84.0	85.3	86.7	88.4	90.0	91.8	93.9	95.9	98.1	100.3	102.8	105.4	108.0
15000	79.8	79.8	80.8	81.8	83.1	84.4	85.8	87.4	89.1	90.9	92.9	94.9	97.1	99.4	101.9	104.5	107.1
17000	79.2	79.2	80.1	81.1	82.4	83.6	85.0	86.6	88.3	90.1	92.1	94.2	96.3	98.6	101.1	103.6	106.3
19000	78.5	78.5	79.5	80.5	81.6	82.9	84.2	85.9	87.6	89.4	91.4	93.5	95.6	97.8	100.2	102.7	105.3
21000	78.0	78.0	79.0	80.0	81.1	82.4	83.8	85.4	87.1	88.8	90.8	92.9	95.0	97.1	99.6	102.1	104.6
23000	77.7	77.7	78.6	79.6	80.7	82.0	83.4	85.1	86.7	88.4	90.4	92.5	94.7	96.9	99.2	101.7	104.3
25000	77.4	77.4	78.2	79.2	80.4	81.7	83.1	84.7	86.5	88.2	90.2	92.3	94.3	96.4	98.8	101.4	104.1
27000	77.3	77.3	78.2	79.1	80.2	81.5	82.8	84.3	86.0	87.7	89.5	91.6	93.8	96.0	98.4	101.1	103.8
29000	77.2	77.2	77.9	78.8	79.9	81.2	82.4	83.8	85.5	87.3	89.2	91.4	93.6	96.0	98.4	101.2	104.1
31000	77.3	77.3	77.9	78.9	79.9	81.1	82.4	83.8	85.6	87.5	89.4	91.6	93.9	96.4	98.9	101.8	105.1
33000	77.7	77.7	78.2	79.1	80.1	81.4	82.7	84.2	86.0	87.8	89.8	92.2	94.8	97.5	100.8	104.4	110.2
35000	78.5	78.5	78.8	79.8	80.8	82.1	83.5	85.0	86.9	89.0	91.1	93.9	98.1	102.8	109.4	112.6	112.7
37000	80.4	80.4	80.7	81.6	82.5	83.8	85.4	87.1	89.1	92.8	97.2	102.7	102.1	102.1	102.2	102.2	102.2
39000	84.3	84.3	84.3	84.8	86.0	87.2	89.4	91.8	90.2	90.3	90.4	90.4	90.5	90.5	90.5	90.6	90.6

Cruise																
Altitude (ft)	280	285	290	295	300	305	310	315	320	325	330	335	340	345	350	400
1000	111.7	114.6	117.6	120.8	123.9	127.2	130.6	134.1	137.8	141.6	145.4	149.3	153.3	157.6	162.0	162.0
11000	111.7	114.6	117.6	120.8	123.9	127.2	130.6	134.1	137.8	141.6	145.4	149.3	153.3	157.6	162.0	162.0
13000	110.7	113.6	116.7	119.8	123.0	126.3	129.6	133.1	136.7	140.4	144.3	148.4	152.6	156.9	161.2	161.2
15000	109.8	112.7	115.7	118.9	122.1	125.4	128.6	132.0	135.7	139.6	143.6	147.7	151.8	156.1	160.4	160.4
17000	108.9	111.7	114.7	117.8	120.9	124.2	127.7	131.2	134.9	138.8	142.8	146.9	151.0	155.5	160.1	160.1
19000	107.9	110.6	113.6	116.8	120.1	123.5	127.0	130.5	134.2	138.1	142.1	146.4	150.9	155.5	160.4	160.4
21000	107.3	110.1	113.1	116.4	119.6	123.0	126.5	130.1	133.8	137.8	142.1	146.7	151.5	156.3	162.0	162.0
23000	107.0	109.8	112.8	116.1	119.3	122.8	126.4	130.1	134.1	138.5	142.9	147.8	153.9	161.9	169.2	169.2
25000	106.7	109.5	112.5	115.8	119.4	123.0	126.9	130.9	134.9	140.0	147.1	155.6	158.6	158.6	158.6	158.6
27000	106.6	109.7	112.9	116.4	120.1	124.0	128.5	134.3	142.5	150.1	149.5	149.5	149.5	149.6	149.6	149.6
29000	107.2	110.3	113.9	117.9	123.0	130.5	139.3	140.3	140.4	140.4	140.4	140.4	140.4	140.4	140.5	140.5
31000	108.8	113.0	119.0	128.2	131.1	131.1	131.2	131.2	131.2	131.2	131.2	131.3	131.3	131.3	131.3	131.3
33000	118.7	121.6	121.7	121.7	121.7	121.7	121.8	121.8	121.8	121.8	121.8	121.8	121.8	121.9	121.9	121.9
35000	112.7	112.7	112.7	112.8	112.8	112.8	112.8	112.8	112.9	112.9	112.9	112.9	112.9	112.9	112.9	112.9
37000	102.3	102.3	102.3	102.3	102.4	102.4	102.4	102.4	102.4	102.5	102.5	102.5	102.5	102.5	102.5	102.5
39000	90.6	90.7	90.7	90.7	90.7	90.7	90.8	90.8	90.8	90.8	90.8	90.8	90.9	90.9	90.9	90.9

Table E.2 Climb Fuelburn by Altitude and Aircraft Class [30]

FL	Aircraft Class:	4J/H	4J/L	3J/H	3J/L	3J/S+	2J/H	2J/LH	2J/L	J/L	2J/LS	2J/S+	J/S+	2J/S	1J/L	1J/S+	1J/S	4T/L	3T/L
	Aliased Class:									2J/L			2J/S+		2J/S+	2J/S	2J/S		2T/L
		FuelBurn Rate (kg/min)																	
0		481.5	117.6	254.1	109.3	41.0	319.6	177.5	89.9	89.9	101.5	27.4	27.4	10.3	27.4	10.3	10.3	58.6	18.0
5		477.2	116.6	252.0	108.5	40.6	316.2	175.8	89.0	89.0	100.0	27.1	27.1	10.2	27.1	10.2	10.2	59.9	17.9
10		473.0	115.6	249.9	107.7	40.2	312.8	174.1	88.2	88.2	98.4	26.8	26.8	10.2	26.8	10.2	10.2	59.5	17.8
15		468.9	115.8	250.7	108.2	39.7	310.1	172.9	87.7	87.7	97.1	26.7	26.7	10.5	26.7	10.5	10.5	59.2	17.7
20		464.7	114.8	248.6	107.4	39.3	306.8	171.2	86.8	86.8	95.6	26.5	26.5	10.5	26.5	10.5	10.5	58.9	17.5
30		456.9	117.6	255.7	111.3	38.5	302.7	169.9	86.8	86.8	93.5	26.6	26.6	11.7	26.6	11.7	11.7	58.2	17.2
40		449.2	122.7	268.2	117.9	37.7	299.9	169.7	87.6	87.6	91.9	27.2	27.2	13.6	27.2	13.6	13.6	57.6	16.9
60		436.9	130.3	270.0	125.1	36.1	291.7	166.3	87.9	87.9	88.9	28.4	28.4	16.2	28.4	16.2	16.2	56.4	16.4
80		420.2	125.7	261.1	121.3	34.5	279.1	159.6	84.4	84.4	83.3	27.2	27.2	16.1	27.2	16.1	16.1	55.1	15.8
100		403.6	121.2	252.1	117.4	33.0	266.8	152.9	81.0	81.0	77.9	26.0	26.0	15.9	26.0	15.9	15.9	53.9	15.2
120		384.2	125.5	275.8	125.9	31.5	260.1	150.3	80.5	80.5	73.6	24.9	24.9	15.7	24.9	15.7	15.7	52.8	14.6
140		367.8	120.9	266.1	121.7	30.1	248.3	143.7	77.1	77.1	68.7	23.9	23.9	15.4	23.9	15.4	15.4	51.7	14.0
160		351.5	116.3	256.5	117.5	28.7	236.8	137.2	73.7	73.7	64.1	22.8	22.8	15.2	22.8	15.2	15.2	50.6	13.5
180		335.3	111.9	246.9	113.3	27.4	225.6	130.8	70.5	70.5	59.8	21.8	21.8	15.0	21.8	15.0	15.0	49.5	13.0
200		319.2	107.1	237.3	109.0	26.1	214.7	124.5	67.3	67.3	55.7	20.9	20.9	14.7	20.9	14.7	14.7	48.5	12.5
220		303.2	102.1	227.9	104.7	24.9	204.1	118.3	64.1	64.1	51.9	19.9	19.9	14.4	19.9	14.4	14.4	47.6	12.0
240		287.2	97.3	218.6	100.3	23.7	193.7	112.2	61.1	61.1	48.5	18.9	18.9	14.1	18.9	14.1	14.1	46.6	11.5
260		271.4	92.5	209.3	95.9	22.6	183.7	106.1	58.0	58.0	45.1	17.9	17.9	13.7	17.9	13.7	13.7	45.8	11.0
280		255.6	88.0	199.5	91.5	21.5	173.9	100.1	54.7	54.7	42.0	17.0	17.0	13.3	17.0	13.3	13.3	45.0	9.8
300		240.8	83.1	188.2	86.6	20.4	164.4	94.3	51.4	51.4	39.1	16.2	16.2	12.9	16.2	12.9	12.9	44.2	9.4
320		225.5	77.7	175.4	80.6	19.5	154.5	87.9	48.1	48.1	36.6	15.4	15.4	12.5	15.4	12.5	12.5	43.5	7.3
340		210.0	72.6	162.7	74.0	18.5	144.6	81.4	44.9	44.9	34.5	14.6	14.6	11.8	14.6	11.8	11.8	42.9	7.0
360		194.7	67.8	150.6	67.5	17.6	135.1	75.1	41.7	41.7	32.6	13.7	13.7	10.8	13.7	10.8	10.8	42.4	6.0
380		179.4	63.4	139.9	61.7	16.8	126.2	69.1	38.8	38.8	31.1	13.0	13.0	10.0	13.0	10.0	10.0	42.2	4.1
400		164.3	59.3	129.6	56.1	16.0	117.6	63.2	36.0	36.0	29.9	12.3	12.3	9.2	12.3	9.2	9.2	42.2	3.9

FL	Aircraft Class:	2T/L	T/L	2T/S+	T/S+	2T/S	T/S	1T/S+	1T/S	4P/L	3P/S	2P/L	2P/S+	P/S+	2P/S	P/S	1P/S+	1P/S	SST	8J/H
	Aliased Class:		2T/L		2T/S+		2T/S	2T/S	2T/S	2P/S	2P/S	2P/S	2P/S	2P/S		2P/S	1P/S		4J/H	4J/H
		FuelBurn Rate (kg/min)																		
0		18.0	18.0	10.1	10.1	5.6	5.6	5.6	5.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	481.5	481.5
5		17.9	17.9	10.2	10.2	5.6	5.6	5.6	5.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	477.2	477.2
10		17.8	17.8	10.2	10.2	5.6	5.6	5.6	5.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	473.0	473.0
15		17.7	17.7	10.2	10.2	5.7	5.7	5.7	5.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	468.9	468.9
20		17.5	17.5	10.1	10.1	5.6	5.6	5.6	5.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	464.7	464.7
30		17.2	17.2	10.0	10.0	5.5	5.5	5.5	5.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	456.9	456.9
40		16.9	16.9	9.8	9.8	5.4	5.4	5.4	5.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	449.2	449.2
60		16.4	16.4	9.5	9.5	5.2	5.2	5.2	5.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	436.9	436.9
80		15.8	15.8	9.2	9.2	5.1	5.1	5.1	5.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	420.2	420.2
100		15.2	15.2	8.9	8.9	4.9	4.9	4.9	4.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	403.6	403.6
120		14.6	14.6	8.7	8.7	4.7	4.7	4.7	4.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	384.2	384.2
140		14.0	14.0	8.3	8.3	4.6	4.6	4.6	4.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	367.8	367.8
160		13.5	13.5	8.1	8.1	4.4	4.4	4.4	4.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	351.5	351.5
180		13.0	13.0	7.7	7.7	4.2	4.2	4.2	4.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5	na	na	335.3	335.3
200		12.5	12.5	7.4	7.4	4.1	4.1	4.1	4.1	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	319.2	319.2
220		12.0	12.0	7.0	7.0	4.0	4.0	4.0	4.0	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	303.2	303.2
240		11.5	11.5	6.7	6.7	3.8	3.8	3.8	3.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	287.2	287.2
260		11.0	11.0	6.3	6.3	3.7	3.7	3.7	3.7	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	271.4	271.4
280		9.8	9.8	5.9	5.9	3.5	3.5	3.5	3.5	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	255.6	255.6
300		9.4	9.4	5.5	5.5	3.4	3.4	3.4	3.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	240.8	240.8
320		7.3	7.3	4.4	4.4	3.3	3.3	3.3	3.3	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	225.5	225.5
340		7.0	7.0	2.4	2.4	3.1	3.1	3.1	3.1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	210.0	210.0
360		6.0	6.0	2.3	2.3	3.0	3.0	3.0	3.0	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	194.7	194.7
380		4.1	4.1	2.2	2.2	2.9	2.9	2.9	2.9	na	na	na	na	na	na	na	na	na	179.4	179.4
400		3.9	3.9	2.1	2.1	2.5	2.5	2.5	2.5	na	na	na	na	na	na	na	na	na	164.3	164.3

Table E.3 Cruise Fuelburn by Altitude and Aircraft Class [30]

FL	Aircraft Class:	4J/H	4J/L	3J/H	3J/L	3J/S+	2J/H	2J/LH	2J/L	J/L	2J/LS	2J/S+	J/S+	2J/S	1J/L	1J/S+	1J/S	4T/L	3T/L
	Aliased Class:									2J/L			2J/S+		2J/S+	2J/S	2J/S		2T/L
		Fuel Burn Rate (kg/min)																	
0		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
5		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
10		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
15		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
20		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
30		145.5	45.8	80.3	37.1	16.1	86.0	53.1	30.3	30.3	26.0	11.7	11.7	7.1	11.7	7.1	7.1	40.4	10.7
40		145.5	45.3	80.9	37.4	16.1	86.2	53.2	30.4	30.4	26.0	11.6	11.6	7.2	11.6	7.2	7.2	41.0	10.8
60		145.4	44.2	82.1	38.0	16.0	86.4	53.5	30.6	30.6	26.0	11.5	11.5	7.4	11.5	7.4	7.4	42.3	10.9
80		145.4	43.2	83.3	38.6	16.0	86.6	53.7	30.8	30.8	26.1	11.3	11.3	7.6	11.3	7.6	7.6	43.6	11.1
100		145.3	42.2	84.6	39.2	16.0	86.8	53.9	31.0	31.0	26.1	11.2	11.2	7.8	11.2	7.8	7.8	44.9	11.3
120		166.2	53.8	115.0	56.4	21.0	100.3	59.8	37.6	37.6	31.2	13.9	13.9	7.9	13.9	7.9	7.9	46.4	11.4
140		165.7	54.4	116.6	57.1	20.9	100.4	60.0	37.8	37.8	31.1	14.0	14.0	8.2	14.0	8.2	8.2	47.8	11.6
160		165.2	55.1	118.2	57.9	20.8	100.5	60.3	38.0	38.0	31.1	14.1	14.1	8.4	14.1	8.4	8.4	49.4	11.5
180		164.6	55.7	119.8	58.8	20.6	100.6	60.5	38.1	38.1	31.1	14.2	14.2	8.6	14.2	8.6	8.6	51.0	11.5
200		164.0	56.4	121.4	59.6	20.5	100.8	60.7	38.4	38.4	31.1	14.3	14.3	8.8	14.3	8.8	8.8	52.6	11.2
220		163.4	57.0	123.1	60.5	20.4	100.8	60.9	38.6	38.6	31.1	14.4	14.4	9.0	14.4	9.0	9.0	54.4	10.8
240		162.7	57.7	124.8	61.3	20.2	100.9	61.1	38.8	38.8	30.9	14.4	14.4	9.3	14.4	9.3	9.3	56.2	10.4
260		161.9	57.1	126.3	60.7	20.1	100.9	61.4	38.6	38.6	30.0	14.4	14.4	9.5	14.4	9.5	9.5	56.4	10.0
280		159.3	56.3	124.8	59.8	19.4	101.0	61.6	38.0	38.0	28.9	14.1	14.1	9.8	14.1	9.8	9.8	56.1	9.0
300		157.0	55.5	122.1	59.1	18.1	100.7	61.8	37.0	37.0	27.5	13.6	13.6	10.1	13.6	10.1	10.1	55.8	8.7
320		154.1	53.1	119.9	57.4	16.9	98.4	60.9	35.9	35.9	26.4	13.1	13.1	10.3	13.1	10.3	10.3	54.8	6.9
340		151.3	50.4	116.3	55.0	15.8	96.0	59.5	34.8	34.8	25.4	12.5	12.5	10.1	12.5	10.1	10.1	52.2	6.6
360		148.0	48.1	113.8	53.0	14.8	93.6	58.6	33.8	33.8	24.7	11.9	11.9	9.7	11.9	9.7	9.7	49.7	5.9
380		144.8	46.5	112.9	50.3	14.0	92.0	58.4	33.2	33.2	24.2	11.5	11.5	9.4	11.5	9.4	9.4	47.6	4.1
400		139.1	45.3	111.8	47.8	13.3	91.2	58.8	32.0	32.0	23.9	11.1	11.1	8.7	11.1	8.7	8.7	45.6	4.0

FL	Aircraft Class:	2T/L	T/L	2T/S+	T/S+	2T/S	T/S	1T/S+	1T/S	4P/L	3P/S	2P/L	2P/S+	P/S+	2P/S	P/S	1P/S+	1P/S	SST	8J/H
	Aliased Class:		2T/L		2T/S+		2T/S	2T/S	2T/S	2P/S	2P/S	2P/S	2P/S	2P/S		2P/S	1P/S		4J/H	4J/H
		Fuel Burn Rate (kg/min)																		
0		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
5		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
10		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
15		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
20		na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na	na
30		10.7	10.7	6.0	6.0	4.3	4.3	4.3	4.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	145.5	145.5
40		10.8	10.8	6.1	6.1	4.3	4.3	4.3	4.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	145.5	145.5
60		10.9	10.9	6.3	6.3	4.4	4.4	4.4	4.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	145.4	145.4
80		11.1	11.1	6.5	6.5	4.4	4.4	4.4	4.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	145.4	145.4
100		11.3	11.3	6.7	6.7	4.4	4.4	4.4	4.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	145.3	145.3
120		11.4	11.4	6.6	6.6	3.9	3.9	3.9	3.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	166.2	166.2
140		11.6	11.6	6.5	6.5	3.9	3.9	3.9	3.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	165.7	165.7
160		11.5	11.5	6.5	6.5	3.9	3.9	3.9	3.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5	0.5	0.5	165.2	165.2
180		11.5	11.5	6.3	6.3	3.8	3.8	3.8	3.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	na	na	164.6	164.6
200		11.2	11.2	6.0	6.0	3.6	3.6	3.6	3.6	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	164.0	164.0
220		10.8	10.8	5.8	5.8	3.5	3.5	3.5	3.5	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	163.4	163.4
240		10.4	10.4	5.6	5.6	3.3	3.3	3.3	3.3	1.8	1.8	1.8	1.8	1.8	1.8	1.8	na	na	162.7	162.7
260		10.0	10.0	5.4	5.4	3.2	3.2	3.2	3.2	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	161.9	161.9
280		9.0	9.0	5.2	5.2	3.1	3.1	3.1	3.1	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	159.3	159.3
300		8.7	8.7	5.0	5.0	3.0	3.0	3.0	3.0	1.4	1.4	1.4	1.4	1.4	1.4	1.4	na	na	157.0	157.0
320		6.9	6.9	4.0	4.0	2.9	2.9	2.9	2.9	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	154.1	154.1
340		6.6	6.6	1.8	1.8	2.8	2.8	2.8	2.8	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	151.3	151.3
360		5.9	5.9	1.7	1.7	2.7	2.7	2.7	2.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	148.0	148.0
380		4.1	4.1	1.7	1.7	2.6	2.6	2.6	2.6	na	na	na	na	na	na	na	na	na	144.8	144.8
400		4.0	4.0	1.7	1.7	2.2	2.2	2.2	2.2	na	na	na	na	na	na	na	na	na	139.1	139.1

Table E.4 Descent Fuelburn by Altitude and Aircraft Class [30]

FL	Aircraft Class:	4J/H	4J/L	3J/H	3J/L	3J/S+	2J/H	2J/LH	2J/L	J/L	2J/LS	2J/S+	J/S+	2J/S	1J/L	1J/S+	1J/S	4T/L	3T/L
	Aliased Class:									2J/L			2J/S+		2J/S+	2J/S	2J/S		2T/L
		Fuel Burn Rate (kg/min)																	
0		40.2	43.5	37.6	22.7	13.9	25.0	18.4	11.9	11.9	15.1	9.8	9.8	4.2	9.8	4.2	4.2	18.1	6.6
5		39.9	43.2	37.3	22.7	13.7	24.9	18.3	11.9	11.9	15.1	9.7	9.7	4.2	9.7	4.2	4.2	18.0	6.5
10		39.5	42.9	37.1	22.6	13.5	24.7	18.3	11.9	11.9	15.1	9.6	9.6	4.2	9.6	4.2	4.2	17.8	6.5
15		39.2	42.6	36.8	22.6	13.3	24.6	18.3	11.9	11.9	15.1	9.5	9.5	4.2	9.5	4.2	4.2	17.7	6.5
20		38.9	42.2	36.5	22.5	13.1	24.4	18.2	11.9	11.9	15.1	9.4	9.4	4.2	9.4	4.2	4.2	17.6	6.5
30		38.3	41.5	35.9	22.4	12.7	24.1	18.2	11.8	11.8	15.0	9.2	9.2	4.2	9.2	4.2	4.2	17.3	6.4
40		37.6	40.9	35.3	22.3	12.3	23.8	18.1	11.8	11.8	15.0	9.1	9.1	4.2	9.1	4.2	4.2	17.1	6.4
60		36.2	39.6	34.2	22.1	11.5	23.3	18.0	11.8	11.8	14.9	8.7	8.7	4.1	8.7	4.1	4.1	16.6	6.3
80		34.9	38.2	33.0	21.9	10.7	22.7	17.9	11.7	11.7	14.9	8.3	8.3	4.1	8.3	4.1	4.1	16.1	6.2
100		33.5	36.9	31.9	21.7	10.0	22.1	17.7	11.7	11.7	14.8	8.0	8.0	4.1	8.0	4.1	4.1	15.6	6.1
120		32.2	35.6	30.8	21.5	9.2	21.5	17.6	11.7	11.7	14.7	7.6	7.6	4.0	7.6	4.0	4.0	15.1	6.0
140		30.8	34.3	29.6	21.3	8.4	20.9	17.5	11.6	11.6	14.7	7.2	7.2	4.0	7.2	4.0	4.0	14.6	5.9
160		29.5	33.0	28.5	21.1	7.6	20.4	17.4	11.6	11.6	14.6	6.8	6.8	4.0	6.8	4.0	4.0	14.1	6.0
180		28.1	31.7	27.3	20.9	6.9	19.8	17.2	11.5	11.5	14.5	6.5	6.5	4.0	6.5	4.0	4.0	13.6	6.0
200		25.8	30.4	26.2	20.7	6.5	19.2	17.1	11.5	11.5	14.4	6.1	6.1	3.9	6.1	3.9	3.9	13.1	5.9
220		24.4	29.0	25.0	20.5	6.2	18.6	17.0	11.5	11.5	14.4	5.9	5.9	3.9	5.9	3.9	3.9	12.6	5.8
240		23.1	27.7	23.9	20.3	5.9	18.0	16.9	11.4	11.4	14.3	5.6	5.6	3.9	5.6	3.9	3.9	12.1	5.7
260		21.7	26.4	22.7	20.1	5.6	17.5	16.7	13.1	13.1	14.2	5.3	5.3	5.4	5.3	5.4	5.4	11.6	5.6
280		20.4	25.1	21.6	19.9	5.4	16.8	16.6	12.9	12.9	14.2	6.6	6.6	5.2	6.6	5.2	5.2	11.1	5.0
300		40.4	23.7	20.4	19.7	5.1	16.3	16.5	16.4	16.4	14.1	7.9	7.9	4.9	7.9	4.9	4.9	10.6	5.0
320		37.7	22.4	19.3	19.5	4.9	15.7	16.3	15.8	15.8	17.2	7.7	7.7	4.5	7.7	4.5	4.5	10.1	4.0
340		35.0	21.1	18.2	19.3	4.6	15.1	16.2	15.2	15.2	16.8	7.3	7.3	4.2	7.3	4.2	4.2	9.6	4.0
360		52.8	19.8	17.0	19.1	4.4	15.1	16.1	14.6	14.6	16.4	6.9	6.9	3.9	6.9	3.9	3.9	9.1	3.6
380		48.8	18.5	15.9	18.9	4.2	14.3	16.0	14.1	14.1	16.0	6.6	6.6	3.6	6.6	3.6	3.6	8.6	2.7
400		44.7	17.1	14.7	18.7	4.0	13.6	15.8	13.6	13.6	15.7	6.4	6.4	3.6	6.4	3.6	3.6	8.1	2.7

FL	Aircraft Class:	2T/L	T/L	2T/S+	T/S+	2T/S	T/S	1T/S+	1T/S	4P/L	3P/S	2P/L	2P/S+	P/S+	2P/S	P/S	1P/S+	1P/S	SST	8J/H
	Aliased Class:		2T/L		2T/S+		2T/S	2T/S	2T/S	2P/S	2P/S	2P/S	2P/S	2P/S		2P/S	1P/S		4J/H	4J/H
		Fuel Burn Rate (kg/min)																		
0		6.6	6.6	4.5	4.5	3.2	3.2	3.2	3.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	40.2	40.2
5		6.5	6.5	4.5	4.5	3.2	3.2	3.2	3.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	39.9	39.9
10		6.5	6.5	4.5	4.5	3.2	3.2	3.2	3.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	39.5	39.5
15		6.5	6.5	4.5	4.5	3.2	3.2	3.2	3.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	39.2	39.2
20		6.5	6.5	4.4	4.4	3.1	3.1	3.1	3.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	38.9	38.9
30		6.4	6.4	4.4	4.4	3.1	3.1	3.1	3.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	38.3	38.3
40		6.4	6.4	4.4	4.4	3.0	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	37.6	37.6
60		6.3	6.3	4.3	4.3	2.9	2.9	2.9	2.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	36.2	36.2
80		6.2	6.2	4.2	4.2	2.8	2.8	2.8	2.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	34.9	34.9
100		6.1	6.1	4.1	4.1	2.7	2.7	2.7	2.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	33.5	33.5
120		6.0	6.0	4.1	4.1	2.6	2.6	2.6	2.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	32.2	32.2
140		5.9	5.9	4.0	4.0	2.5	2.5	2.5	2.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	30.8	30.8
160		6.0	6.0	3.9	3.9	2.4	2.4	2.4	2.4	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.3	0.3	29.5	29.5
180		6.0	6.0	3.9	3.9	2.3	2.3	2.3	2.3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	na	na	28.1	28.1
200		5.9	5.9	3.8	3.8	2.2	2.2	2.2	2.2	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	25.8	25.8
220		5.8	5.8	3.7	3.7	2.1	2.1	2.1	2.1	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	24.4	24.4
240		5.7	5.7	3.6	3.6	1.9	1.9	1.9	1.9	0.7	0.7	0.7	0.7	0.7	0.7	0.7	na	na	23.1	23.1
260		5.6	5.6	3.6	3.6	1.8	1.8	1.8	1.8	0.5	0.5	0.5	0.5	0.5	0.5	0.5	na	na	21.7	21.7
280		5.0	5.0	3.5	3.5	1.7	1.7	1.7	1.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	na	na	20.4	20.4
300		5.0	5.0	3.4	3.4	1.6	1.6	1.6	1.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	na	na	40.4	40.4
320		4.0	4.0	2.7	2.7	1.5	1.5	1.5	1.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	na	na	37.7	37.7
340		4.0	4.0	1.3	1.3	1.3	1.3	1.3	1.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	na	na	35.0	35.0
360		3.6	3.6	1.3	1.3	1.2	1.2	1.2	1.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	na	na	52.8	52.8
380		2.7	2.7	1.3	1.3	1.1	1.1	1.1	1.1	na	na	na	na	na	na	na	na	na	48.8	48.8
400		2.7	2.7	1.3	1.3	0.9	0.9	0.9	0.9	na	na	na	na	na	na	na	na	na	44.7	44.7

Table E.5 BADA-based [38] Fuel Scale Factor Assumptions

Aircraft Type (ICAO)	Initial Weight (lb)	Weight Class	Mach	Altitude (ft)	Fuel Scale Factor
A300	275575	H	0.78	38000	0.5140
A310	264552	H	0.80	41000	0.4025
A320	136685	L	0.78	39000	0.8303
A330	352736	H	0.80	41000	0.4596
A340	440920	H	0.80	40000	0.6303
ATP	44092	L	0.40	21000	0.3290
ATR	33069	S	0.45	25000	0.2688
B707	220460	H	0.80	42000	0.5297
B727	163140	L	0.82	33000	1.4941
B73A	101412	L	0.72	37000	0.8532
B73B	119048	L	0.74	37000	0.8649
B73C	136906	L	0.79	43000	1.1480
B74A	617288	H	0.82	36000	1
B74B	661380	H	0.85	39000	1.0615
B757	209437	H	0.78	39000	0.3290
B767	330690	H	0.80	39000	0.4508
B777	465171	H	0.84	43100	0.7198
BA11	69886	L	0.72	35000	0.5697
BA46	79366	L	0.70	31000	0.8093
BE20	11010	S	0.48	32000	0.0538
BE99	9039	S	0.35	15000	0.1417
BE9L	8025	S	0.40	31000	0.1076
C130	129983	L	0.50	30000	1.4601
C160	88184	L	0.38	30000	0.6522
C421	6261	S	0.33	18500	0.1217
C550	13228	S	0.63	38000	0.2382
C560	13977	S	0.73	45000	0.2011
CARJ	46297	L	0.74	38000	0.3569
CL60	34061	L	0.77	41000	0.2541
D228	12346	S	0.34	29600	0.3082
D328	26455	S	0.59	32800	0.2596
DC10	374782	H	0.82	39000	0.5640
DC8	242506	H	0.80	42000	0.3149

Aircraft Type (ICAO)	Initial Weight (lb)	Weight Class	Mach	Altitude (ft)	Fuel Scale Factor
DC9	100089	L	0.80	35000	0.9943
DHC8	37478	L	0.45	25000	0.2065
E120	22046	S	0.47	32000	0.1735
F100	83775	L	0.70	35000	0.6606
F27	37478	L	0.37	20000	0.3972
F28	52910	L	0.70	35000	0.4969
F50	39683	L	0.44	25000	0.3261
F70	74956	L	0.70	37000	0.6218
F900	33951	L	0.80	44000	0.2607
FA10	15983	S	0.75	45000	0.1510
FA20	22046	S	0.76	42000	0.3128
FA50	33069	S	0.75	49000	0.2540
H25B	18001	S	0.75	41000	0.3433
JSTA	13669	S	0.41	25000	0.1681
JSTB	19841	S	0.42	26000	0.1924
L101	340611	H	0.82	40000	0.5160
LJ35	14991	S	0.77	38000	0.1959
MD11	501106	H	0.83	37000	0.7604
MD80	134922	L	0.76	37000	1
MU2	8988	S	0.57	28000	0.1126
P31T	7981	S	0.44	29000	0.1146
PA27	4806	S	0.50	10000	0.0659
PA28	2326	S	0.18	10000	0.0157
PA31	5489	S	0.33	20000	0.1284
PA34	4564	S	0.34	15000	0.1268
PA42	9101	S	0.46	33000	0.1182
SB20	44092	L	0.62	31000	0.3745
SF34	22046	S	0.45	31000	0.3367
SH36	24912	S	0.33	20000	0.2323
SW3	10582	S	0.52	31000	0.1371
T134	92593	L	0.78	37000	0.7185
T154	187391	L	0.80	41000	1.5321
TRIN	2943	S	0.35	8000	0.0302

Note: Heavy aircraft normalized to B747 fuelburn rates, all others normalized to MD80 fuelburn rates (lbs/nm)

References

[1] NASA, "AATT Program Products Descriptions," Draft Manuscript, Advanced Air Transportation Technologies (AATT) Program Office, NASA Ames Research Center. (June 1998)

[2] RTCA Task Force 3, "Final Report of RTCA Task Force 3: Free Flight Implementation," RTCA, Inc. (October 1995)

[3] Swensen, H., et al, "Design & Operational Evaluation of the Traffic Management Advisor at the Fort Worth ARTCC," 1st USA/Europe ATM R&D Seminar, France. (June 1997)

[4] Green, S.M., and Vivona, R., "En route Descent Advisor (EDA) Concept," Advanced Air Transportation Technologies (AATT) Project Milestone 5.10 Report, NASA Ames Research Center. (September 1999)

[5] Weidner, T., Schleicher, D., Coppenbarger, R., "NASA/FAA En Route Data Exchange (EDX) Phase 2 Field Evaluation Project Plan, " Seagull Technology, TR99185.04-01. (February 2000)

[6] Green, S., Goka, T., Williams, D., "Enabling User Preferences through Data Exchange," AIAA GNC Conference. (August 1997)

[7] Couluris, G., Weidner, T., Sorensen, J., "Final Approach Enhancement and Descent Trajectory Negotiation, Potential Benefits Analysis," Seagull Technology, TR97142-02. (July 1997).

[8] Couluris, G. , Weidner, T. Sorensen, J., "Initial Air Traffic Management (ATM) Enhancement Potential Benefits Analysis," Seagull Technology, TR96151-01. (September 1996)

[9] Weidner, T., Couluris, G., Sorensen, J., "Initial Data Link Enhancement to CTAS Build 2 Potential Benefits Analysis," Seagull Technology, TR98151-01. (June 1998)

[10] Weidner, T., Davidson, T.G., "Preliminary En Route Data Exchange Potential Benefits Assessment," Seagull Technology, TR98175.9-01. (December 1998)

[11] Weidner, T., "Capacity-Related Benefits of Proposed CNS/ATM Technologies," 2nd USA/Europe Air Traffic Management R&D Seminar (ATM98). (December 1998)

[12] Weidner, T., Davidson, G., Coppenbarger, R. Green, S., "Modeling ATM Interruption Benefits," AIAA99-4296, AIAA GNC Conference. (June 1999)

[13] Weidner, T., et al, "EDA and EDX ATM Interruption Benefits," TR98188.26-01f, Seagull Technology. (December 2000)

[14] Weidner, T., et al, "Potential Benefits of User-Preferred Descent Speed Profile," TR98188.26-01f, Seagull Technology. (December 2000)

[15] Celio, J., Bowen, K., Winokur, D., Lindsay, K., Newberger, E., Sicenavage, D., "Free Flight Phase 1 Conflict Probe Operational Description," MITRE Technical Report MTR 0W00000100. (March 2000)

[16] FMS-ATM Next Generation (FANG) Team, "FANG Operational Concept," FAA and Boeing Commercial Airplane Group CRDA 93-CRDA-0034. (February 1996)

[17] FMS-ATM Next Generation (FANG) Team, "FMS-ATM Next Generation (FANG) Required Capabilities," DOT/FAA/AND-98-14, FAA. (November 1998)

[18] Mueller, T., Weidner, T., "Enhanced Surveillance Data Link Study Plan," TR00184.01-01, Seagull Technology. (June 2000)

[19] Green, S., Unpublished Results of NASA TS simulations of B73S Climb Trajectories, NASA Ames Research Center, Moffett Field, CA. (August 1997)

[20] Green, S., Vivona, R., and Grace, M., "Field Evaluation of Descent Advisor Trajectory Prediction Accuracy for En route Clearance Advisories," AIAA-98-4479, AIAA GNC Conference. (August 1998)

[21] Bilimoria, K., Communication, EDX Phase 2 Data Prioritization meeting, NASA Ames Research Center, Moffett Field, CA. (June 1998)

[22] Crown Communications, Inc., "Center TRACON Automation Traffic Management Advisor Build 2 (TMA) Assessment - Final Report," Doc. No. CTASDS-BAPRPT-003, FAA. (December 1996)

[23] Coppenbarger, R.A., "Enroute Climb Trajectory Prediction Enhancement Using Airline Flight-Planning Information,"AIAA99-4147, Guidance Navigation & Control Conference. (August 1999)

[24] Eurocontrol, "Study of the Acquisition of Data from Aircraft Operators to Aid Trajectory Prediction Calculation," EEC Note No. 18/98. (September 1998)

[25] Davidson, T.G., Birtcil, L., "Comparison of Fuel Optimal, CTAS and FMS Time-of-Arrival Control Strategies for MD-80 Aircraft Trajectories," Seagull TR178-02. (September 98)

[26] Davidson, T.G., Birtcil, L., "Comparison of Fuel Optimal, CTAS and FMS Time-of-Arrival Control Strategies for B-747 Aircraft Trajectories," Seagull TR178-03 (September 98)

[27] Davidson, T.G., Birtcil, L., Green, S., "Comparison of CAS/EDA and FMS Time-of-Arrival Control Strategies," AIAA99-4230, Guidance, Navigation, and Control Conference. (August 1999)

[28] Davidson, T.G., Weidner, T., Birtcil, L., "En Route Descent Advisor Potential Benefits Assessment," TR98175.6-01, Seagull Technology. (December 1998)

[29] Davidson, T.G., Birtcil, L., "Sector Tools Potential Benefits Analysis," Seagull TR98154-01D. (draft April 1998)

[30] Couluris, G., Weidner, T., "Terminal Airspace Decision Support Tool Functions, Preliminary Potential Benefits Analysis," Seagull Technology, TR99185.02-01. (December 1999)

[31] Hunter, G., Weidner, T., Couluris, G., Sorensen, J., Bortins, R., " CTAS Error Sensitivity, Fuel Efficiency, and Throughput Benefits Analysis," Seagull Technology TR96150-02. (July 1996)

[32] Visits and consultations with Atlanta, Fort Worth, Los Angeles, and New York ARTCCs and Atlanta, Dallas-Fort Worth, Southern California, and New York TRACONs (July 1999).

[33] CSSI Inc. , "Traffic Demand Scenarios" computer data files. (September 1998)

[34] Sorensen, J., Shen, M., Hunter, G., "Analysis of Final Approach Spacing Requirements, Part I," TR91112-01, Seagull Technology. (January 1991)

[35] Federal Aviation Administration (FAA), "1997 Aviation Capacity Enhancement Plan," Office of System Capacity. (December 1997)

[36] FAA, "1997 Terminal Area Forecast (TAF) System," Office of Aviation Policy and Plans, FAA APO Home Page, Internet WWW Site. (October 1998)

[37] Weidner, T., Green, S., "Modeling ATM Automation Metering Conformance Benefits," 3rd USA / Europe Air Traffic Management R&D Seminar (ATM00). (July 2000)

[38] Eurocontrol Experimental Centre, "User Manual for the Base of Aircraft Data (BADA) Revision 3.1," EED Note No. 23/97, Eurocontrol. (October 1998)

[39] MD80, American Airlines Operation Engineering. (1998)

[40] United 747 Flight Manual, p.816, Operating Speeds. (January 1988)

[41] Benjamin, Stanley G., et al, "Aviation Forecasts From the RUC-2," 8th Conference on Aviation, Range, and Aerospace Meteorology, Dallas. (January 1999)

[42] Williams, D., Green, S., "Flight Evaluation of Center-TRACON Automation System Trajectory Prediction Process," NASA/TP-1998-208439. (July 1998)

[43] Green, S., and Vivona, R., "Field Evaluation of Descent Advisor Trajectory Prediction Accuracy," AIAA 96-3764. (July 1996)

[44] Kayton, M., and Fried, W.R., "Avionics Navigation Systems," Second Edition, John Wiley & Sons. (1997)

[45] Wanke, C., "Using Air-Ground Data Link and Operator-Provided Planning Data to Improve ATM Decision Support System Performance," IEEE Conference. (1997)

[46] FAA, "Air Traffic Rules and Procedures Service, Air Traffic Control FAA Order 7110.65, USDOT. (1998)

[47] Communication with McNally, B.D., and Bilimoria, K., NASA Ames Research Center. (1999)

[48] Brudnicki, D., McFarland, A., "User Request Evaluation Tool (URET) Conflict Probe Performance and Benefits Assessment," MITRE CAASD, MP 9720000112. (June 1997)

[49] FAA, Air Traffic Activity query, Office of Aviation Policy and Plans (APO) Data System, FAA APO Home Page, Internet WWW Site. (November 1998)

[50] Mukai, C., "Design and Analysis of Aircraft Dynamics Models for the ATC Simulation at NASA Ames Research Center," Seagull TR92119-02. (March 1992)

[51] FAA Surveillance Systems Engineering Group (SSEG) AND-402 website. http://www.faa.gov/and/AND400/and402/402home.htm

[52] Surveillance Systems Engineering Group (SSEG) AND-402, "The Need for ASTERIX in the NAS," The Integrator, Vol.1, No. 5. (May / June 1998)

[53] Shank, E., "High Level Data Flow Description for Proposed Enhanced Surveillance / ASTERIX Benefit Demonstration," Draft, MIT Lincoln Laboratory. (January 1999)

[54] Hawthorne, M., Triantos, J., "FMS-ATM Calibration through Enhanced Surveillance (FACES)," Briefing package. (November 1998)

[55] FAA Aeronautical Data Link Program (ADL) AND-370 website http://38.243.118.34/

[56] FAA Collaborative Decision Making (CDM) website http://www.metsci.com/cdm/index.html

[57] NASA Advanced Air Transportation Technologies (AATT) website http://www.asc.nasa.gov/aatt/

[58] NASA Advanced Air Transportation Technologies (AATT) Project, Aviation System Capacity (ASC) Program, "Concept Definition for Distributed Air/Ground Traffic Management (DAG-TM), version 1.0." (September 1999)

[59] Cole, R., Green, S., Jardin, M., Schwartz, B., Benjamin, S., "Wind Prediction Accuracy for Air Traffic Management Decision Support Tools," 3rd USA / Europe Air Traffic Management R&D Seminar (ATM00). (July 2000).

[60] Kilbourne, T., "Assessment of Air-Ground Applications for Future Integrated Services," performed for RTCA SC194 WG2 under AND-370 support. (July 1999)

[61] RTCA SC169, "Operational Concepts and Data Elements Required to Improve Air Traffic Management (ATM)- Aeronautical Operational Control (AOC) Ground-Ground Information Exchange to Facilitate Collaborative Decision Making," RTCA/DO-241. (October 1997)

[62] Airlines Electronic Engineering Committee (AEEC) Website http://www.arinc.com/Ind_Govt_Srv/AEEC/aeec.html

[63] Eurocontrol Website http://www.eurocontrol.fr/

[64] de Booth, E.M.,"Confirmation of User Requirements (Final Report)," DADI (25 March 1999)

[65] Favennec, B., Salembier, P., ESCAPADE: Display of Downlinked Aircraft Parameters," 2nd USA / Europe Air Traffic Management R&D Seminar. (December 1998)

[66] Federal Aviation Administration, "Ceiling and Climatological Study and System Enhancement Factors," Final Report FAA Office of Aviation System Plans. (June 1975)

[67] FAA, "Economic Values for Evaluation of FAA Investment and Regulatory Programs," FAA-APO-98-8, Office of Aviation Policy and Plans. (June 1998)

[68] FAA, "FAA Aviation Forecasts Fiscal Years 1998-2009," Final Report FAA-APO-98-1, Office of Aviation Policy & Plans. (March 1998)

[69] Cole, R., Green, S., Jardin, M., Schwartz, B., Benjamin, S., "Wind Prediction Accuracy for ATM Decision Support Tools," 3rd USA / Europe Air Traffic Management R&D Seminar (ATM00). (July 2000)

[70] DenBraven, W., "Fully Automated Simulation of Air Traffic Control Concepts," Joint FAA/NASA CTAS/Datalink Workshop. (November 1994)